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# MEASUREMENT OF PERMEABILITY OF POROUS MEDIA[1]

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## ABSTRACT

A detailed technique is described for the measurement of the permeability of porous media, by the use of either liquids or gases. Derivations are given of the formulae by which the permeability may be computed from the laboratory measurements. In addition to defining a convenient permeability unit, it is proposed to call it the "darcy." Field measurements on the effective permeability of underground sands are discussed, and the appropriate formulae are derived. These include expressions for liquid flow, gas flow, gravity flow, and composite artesian and gravity flow in steady state. Correction curves are given for application where the wells do not completely penetrate the producing sands.

## INTRODUCTION

One of the most important advances in petroleum technology is manifested in the rapidly growing efforts of production engineers to apply quantitative methods in their analyses of field production problems. Until recently the only information regarding the characteristics of reservoir rocks which was considered worthy of serious attention concerned those features primarily geological in nature. While the data so obtained sufficed to give essential information regarding the reservoir as a static system, they were quite inadequate when attempting to analyze the flowing characteristics of the system.

The rate of flow of a fluid through any system is dependent upon two fundamental quantities: the pressure gradients applied, and the resistance to flow developed along the channel. The former is obvi-

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[2] Gulf Research Laboratory. The writers wish to express their appreciation to P. D. Foote, director of the laboratory, and to other executives of the Gulf Production Company in granting permission to publish this paper.

ously determined only by the magnitude of the pressure applied, while the latter depends upon the nature of the fluid, of the channel, and under certain conditions, upon the rate of flow. In general, the type of flow may lie between two definite limits. At one extreme is the smooth stream-line motion or "viscous" flow wherein the resistance developed is proportional to the velocity and to the viscosity of the fluid. As the velocity of flow increases, the smooth stream-line motion of the fluid may be broken up by eddies which dissipate energy in addition to that dissipated by the motion in the direction of translation, until at the other extreme of so-called completely "turbulent flow" the resistance developed is proportional to the square of the velocity and is independent of the viscosity of the fluid.

It is obvious that in any case where the flow through a medium may be of a type ranging from viscous to turbulent depending upon the velocity of flow, the resistance factor, or its reciprocal, the *permeability*, can not be a constant and the term "permeability of the medium" is meaningless unless the exact conditions are specified. Fortunately, experiment shows that in the case of the porous media encountered in oil reservoirs, with the possible exception of highly fractured or cavernous formations, the flow of liquids is in the viscous region at velocities which are likely to be attained in practice. Assuming, therefore, that we are dealing only with this type of flow, the resistance factor is a constant and the permeability of the medium may be measured with assurance that it is a constant of the medium and is independent of the velocity of flow.

It is interesting to note that in the case of fluid flow through porous media, unlike that in open conduits, the transition from viscous to turbulent flow is not abrupt with an unstable transition state, but rather as the velocity of flow increases there is a very gradual and stable transition from the viscous to the completely turbulent state, as would be anticipated from the nature of the medium. However, even in the case of gas flow where departures from viscous flow may be quite appreciable, it is doubtful whether the limiting condition of *completely* turbulent flow is actually reached in any ordinary porous formation, even under abnormal operating conditions.

## PERMEABILITY-POROSITY RELATIONS

In view of the occasional indiscriminate use of the terms permeability and porosity and in order to avoid such looseness in the use of the terms, it will not be out of place to define each and point out some prevalent misconceptions regarding the relations between these two factors.

*Porosity.*—The porosity of a porous material is defined as the ratio of the volume of the pore space to the total bulk volume of the material. This ratio or porosity is usually expressed in per cent.

*Permeability.*—The permeability of a porous medium is the volume of a fluid of unit viscosity passing through a unit cross section of the material under a unit pressure gradient in unit time.

There appears to be considerable discussion regarding the relation between permeability and porosity. From the aforementioned definitions, no necessary correlation is implied or is to be expected. While it is true that one would expect a very porous material to be highly permeable, it is not a necessary conclusion since a material may evidently have a high percentage of pore space and yet be quite impermeable because of the lack of interconnection between the pores. Further, while the porosity of a sand is primarily independent of the grain size, it is easily shown that, neglecting cementation, the permeability is a direct function of grain size. The exact relation remains to be found, excepting in the case of sands of uniform grain size where, under similar types of packing, the permeability varies as the square of the grain size. However, in comparing two sands of identical grain size and distribution, equal permeabilities would be expected, excepting in so far as the type of packing, hence the porosity, differs in the two sands. This represents the one condition under which a real primary correlation will be found between permeability and porosity, and only under such circumstances should correlation be expected.

Eventually, it may be found possible to correlate permeability with grain size and distribution, with porosity entering as a secondary factor. At present, excepting for some very special cases or for the academic interest involved, it seems far simpler to make a direct and accurate measurement of the permeability of a sample rather than to carry through a difficult sieve analysis, a porosity determination, and then to make an approximate permeability calculation from a correlation which remains to be found. In fact, it is extremely doubtful that an accurate and generally applicable formula will ever be found which will permit calculation of permeability from the three other factors mentioned.

### CALCULATION OF PERMEABILITY

As suggested by the definition of the term "permeability" given in the introduction, the rate of flow of a fluid through a porous medium, under conditions of viscous flow, is directly proportional to the pressure gradient acting on the fluid.[3] When this statement is ex-

[3] It is of interest to note that this relation, as applied to liquids, dates back to 1856, when H. D'Arcy carried out his series of classic experiments on the flow of water

pressed analytically, the permeability appears simply as the constant of proportionality.

Thus if $v_x$ is the velocity of the fluid (measured as fluid flux across a unit area of the porous medium) in the direction indicated by $x$, and $\partial p/\partial x$ is the pressure gradient at the point to which $v_x$ refers, then the foregoing statement—D'Arcy's law—may be expressed as:

$$v_x = \frac{k}{\mu}\frac{\partial p}{\partial x} \qquad (1)$$

where $k$ is the permeability of the medium and $\mu$ is the viscosity of the fluid. To obtain the permeability, it is only necessary to solve equation 1 for $k$ as:

$$k = (\mu v_x)/\frac{\partial p}{\partial x}\cdot \qquad (1a)$$

A measurement of the permeability, therefore, consists simply in measuring corresponding values of $v_x$ and $\partial p/\partial x$ in a suitable channel of the medium in question and with a fluid of known viscosity. If the channel is a linear column of uniform cross section, with the pressure sensibly constant over the section, the calculation of the required data and their interpretation may be very readily carried out as follows.

In case the permeability is being measured with an incompressible fluid, the velocity $v_x$ must evidently be constant over the whole length of the channel. Consequently, the pressure gradient, $\partial p/\partial x$, must also be uniform along the flow channel, and have in fact the value $(P_1 - P_2)/L$, where $P_1$, $P_2$ are the pressures at the terminae of the segment of the column of length $L$. Further, if the cross-sectional area of the column is $A$ and if $Q$ be the volume of liquid passing through it in unit time, $v_x$ is evidently equal to $Q/A$. Equation 1a then takes the form:

$$k = \frac{\mu Q L}{A(P_1 - P_2)}\cdot \qquad (2)$$

If, however, the permeability measurement is to be made with a gas, the velocity $v_x$ will not be constant, but rather it will increase as the outlet end of the flow channel is approached, due to the expansion of the gas. The pressure gradient, $\partial p/\partial x$, will of course also

through sand layers in water filters. Although the classical hydrodynamics had already been formulated by Navier and Stokes and was formally capable of describing the details of D'Arcy's problem, the analytical difficulties were so tremendous that D'Arcy had no recourse but an appeal to an empirical method of solution. Indeed, it is fortunate that D'Arcy did not wait for a theoretical analysis of the problem, for even now a satisfactory hydrodynamic treatment of the problem appears to be but a futile hope.

increase simultaneously and in such a way that its ratio to $v_x$ remains constant. On the other hand, as shown by Muskat and Botset, the *mass velocity* ($v_x$ multiplied by the density) and the gradient in the *squares* of the pressures do remain constant along the length of the flow channel. In fact, in the notation of equation 2, we have:

$$\frac{\partial p^2}{\partial x} = 2p\frac{\partial p}{\partial x} = \text{const.} = \frac{P_1^2 - P_2^2}{L} = 2\overline{P}\frac{(P_1 - P_2)}{L}$$

where $\overline{P}$ is the *mean* pressure. Inserting this in equation 1a we get:

$$k = \frac{\mu v_x p L}{(P_1 - P_2)\overline{P}} \cdot$$

Hence if $v_x$ is chosen as referring to the mean pressure, so that $p = \overline{P}$, and if we denote by $\overline{Q}$ the total fluid outflow rate, as reduced to $\overline{P}$, we finally obtain:

$$k = \frac{\mu \overline{Q} L}{A(P_1 - P_2)} \cdot \tag{3}$$

Thus $k$ may be computed from gas flow experiments in exactly the same way as in liquid flow experiments, excepting that the volume outflow rate must be reduced to the algebraic mean pressure in the flow channel.

Equations 2 and 3 are the fundamental equations underlying the laboratory determinations of the permeability of porous media. It is important, however, to observe the following point. The foregoing equations apply only to a system in which the flow is viscous. As suggested in the introduction, viscous flow in a sand, by analogy with the corresponding problem in pipes or sand-free vessels, may be qualitatively described as one in which the flow is stream-line and free of eddies. When eddies do form in the system, it is considered to be in a "turbulent" state. Quantitatively, however, "viscous flow" in a sand may best be defined by D'Arcy's law itself, which is the exact analogue of the hydrodynamic relation between the velocity and pressure drop for the viscous flow in a sand-free narrow channel. Hence, when the flow in the system obeys D'Arcy's law, it will be considered as viscous, and when it does not, it will be taken as turbulent.

The test for viscous flow may, therefore, be stated as follows. If the outflow rates, $Q/A$ or $\overline{Q}/A$, are plotted against the pressure differentials across the system and the result is a straight line passing

through the origin,[4] the flow must be viscous, and the slopes of the lines are $k/\mu$. If, on the other hand, the flow is not viscous, the curves plotted as here indicated will not be linear, for if the fluid is dissipating its energy in the form of eddies, the velocities will not rise as rapidly as the pressure gradients, and the curves of $Q/A$ or $\bar{Q}/A$ plotted against $P_1-P_2$ will bend toward the $P_1-P_2$ axis.

Finally, it is to be noted that although the pressure distributions in the columns of porous media used for permeability measurements will be linear with respect to $p$, in the case of liquids, and with respect to $p^2$, in the case of gases, this linearity is not to be used as a criterion for the viscous character of the flow. These pressure distributions are common to both viscous and turbulent states of flow of fluids and are characteristic only of the *linear* character of the flow channel. The $Q/A$ or $\bar{Q}/A$ vs. $\Delta P(P_1-P_2)$ curves must be used as criteria of the viscous or turbulent nature of the flow.

## STANDARDIZATION OF PERMEABILITY DIMENSIONS

As yet there has been no standardization of the units in which to express the permeability constant. In the past $k$ has been expressed in units to which the particular individual or laboratory has become accustomed, or too often the units have not even been specified, thus making the data of little value to other workers. Often the temperature is not stated, and one is at a loss to assign the proper corrections so as to make the data comparable with other corresponding results. Obviously, such a condition must be corrected if the accumulated data on permeabilities are to have a maximum value. For this reason the writers propose for consideration the units which will be used here and have also been used by many others.

From the definition of permeability already given, it is the rate of flow of a fluid of unit viscosity through a unit cross section of the material under a unit pressure gradient and viscous flow conditions. Evidently, the rate of flow, the cross-sectional area, and the pressure gradient may be expressed in a variety of units, and for the purposes of this discussion the writers use the following.

Volume —cubic centimeter
Length —centimeter
Time —second
Pressure —1 atmosphere (76.0 cm. *Hg*)
Viscosity—1 centipoise

[4] The passage through the origin does not refer to the viscous character of the flow; rather it is the condition that the fluid is not plastic.

These units lead to a dimensional expression for the permeability constant:

$$k = \frac{\mu \times \text{cm.}^3 \times \text{cm.}}{\text{sec.} \times \text{cm.}^2 \times \text{atmos.}} = \frac{\mu \times \text{cm.}^2}{\text{sec.} \times \text{atmos.}} = \frac{\text{poises} \times \text{cm.}^4}{\text{sec.} \times \text{dynes}}$$

or expressed in fundamental units, the dimensions are:

$$[k] = [L]^2.$$

The use of the centipoise as a unit of viscosity rather than the poise is of advantage in that it avoids expressing $k$ in inconveniently small numbers, and further since the viscosity of water at 20°C. is 1.005 centipoises, the value of $k$ (standard) would be almost exactly that for water at 20°C.

A further step involving naming the unit would be convenient. The unit of electrical conductivity is called the mho (reciprocal of resistivity; ohm), after Ohm; likewise the unit of permeability might well be called a "darcy" after D'Arcy, who first formulated the law of porous flow. Thus, a statement of the permeability of a sample, $k = 2.00$ darcys means that a rate of flow of 2 cc./sec. is obtained through a cross section of 1 cm.$^2$ and a length of 1 cm. under a pressure differential of 1 atmosphere (76.0 cm. $Hg$) for a fluid of 1 centipoise viscosity.

In view of the fact that extensive permeability work has only started recently, it would not be inconvenient or difficult to introduce at present this or some similar name to replace the lengthy dimensional expression commonly used for the permeability unit. Since D'Arcy's law is the basic law in porous flow and following the precedent set in the case of other physical constants, adoption of the name "darcy" for the standard permeability unit seems only logical.

As a matter of convenience, therefore, all permeabilities are expressed throughout the remainder of this paper in terms of the darcy as defined.

## MEASUREMENT OF PERMEABILITY

It is clear that a measurement of the permeability of a rock sample essentially involves only a proper mounting of the sample whose dimensions are known, with provision for determining the pressure differential across the sample and the rate of flow of the fluid through it. There are, however, many details which must be observed if errors are to be eliminated, and for this reason a detailed description is presented of the technique which has been found most satisfactory from the point of view of both speed and accuracy.

PREPARATION OF SAMPLE

While apparently no limitation is imposed on the size of sample to be used, in order to minimize effects due to very local inhomogeneities in the material such as concretions, small shale streaks, et cetera, the samples should be of generous size. When possible they are cut to a diameter of about 5 cm. and 1 cm. or more in length. Because of the necessity for measuring the permeability, both parallel with, and perpendicular to, the bedding plane, separate samples are cut in each of these directions. A simple slotted brass tube, mounted

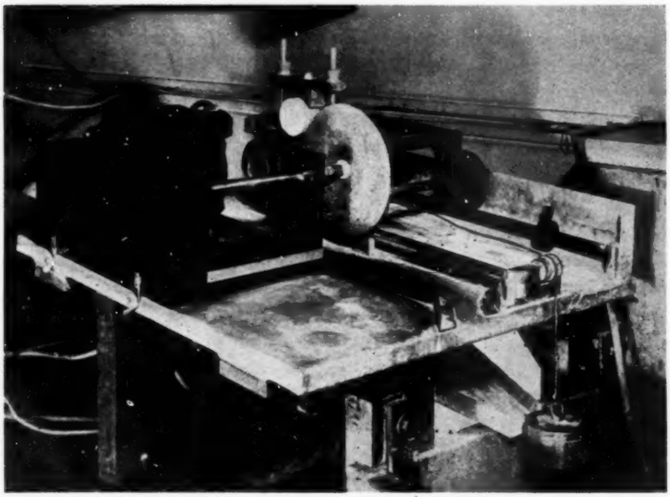

FIG. 1.—Core-cutting machine.

in a slow-speed drill press, is used in cutting out the core. Coarse carborundum, fed to the drill along with a small amount of water, produces a rapid and accurate cut. The core thus obtained is next mounted in a special machine which cuts accurately plane faces on the sample. The cutting disc is a Norton "Crystolon" bakelite-bonded carborundum wheel 7 inches in diameter and 0.0625 inch in thickness, operated at 1,700 R.P.M. A small amount of water is fed continuously to clean the cut. This disc has been found more satisfactory than a metal disc fed with loose carborundum.

Serious errors may occur due to plugging of the sand face by mud if the cutting is not properly done. If a dry core is exposed to the cutting operation, capillary action suffices to force the cutting fluid

carrying fine cuttings into the face, and the result is a very effective mudding of the faces and consequent lowering of the permeability. It was found that by soaking the cores in water before cutting, the capillary effect during cutting is effectively eliminated. Obviously, if the cementing material in the sample is adversely affected by water, some other cutting fluid may be used with the preliminary soaking in the same fluid. The sample is finally carefully cleaned and dried preparatory to mounting.

In order to test the reliability of the cutting method in eliminating mudding of the sand faces, the following method was used. Two samples were cut from adjacent portions of a sandstone block. One sample was faced in the regular way by the cutting machine and the faces of the other sample were prepared by fracturing in a specially constructed press so that the faces were uncontaminated. The permeability of these samples to gas was measured with the results shown in Table I.

TABLE I

| *Sample Cut by* | *Cutting Wheel* | *Fracture* |
|---|---|---|
| $k$ (Sample 1) (darcys) | 0.65 | 0.67 |
| $k$ (Sample 2) (darcys) | 4.83 | 4.83 |

These results, further substantiated by similar data, indicate that with the type of cutting wheel used and the simple precautions taken, no appreciable plugging of the sand face occurs. The effect has been discussed at some length because it is a factor which may be serious, yet easily overlooked, particularly where numbers of cores are prepared for routine measurement.

### EXTRACTION OF OIL FROM SAMPLES

Since many of the samples may contain oil, the sample must be carefully treated in order to remove, as far as possible, all traces of oil content. Since a similar extraction process is required in the more familiar porosity determination methods, it will not be necessary to describe the process in detail. The usual large Soxhlet extraction apparatus using carbon tetrachloride or benzol as a solvent will be found convenient and quite efficient. Since the size of the permeability samples is greater than the usual porosity sample, a considerably greater time is required to extract the contained oil properly. Doubtless some improvement in extraction could be obtained by designing a special apparatus in which the solvent could be forced through the sample under a somewhat greater pressure gradient than obtained by gravity in the Soxhlet extractor, as ordinarily used. The simple expedient has been used of pressing the samples into the bottom end of

a brass tube 15 cm. long, the pressed fit being sufficiently good so that when this tube is inserted in the extractor sample end down, a head of fluid which may be as high as 15 cm., is maintained to force the solvent through the sample. The use of a small amount of plaster of paris

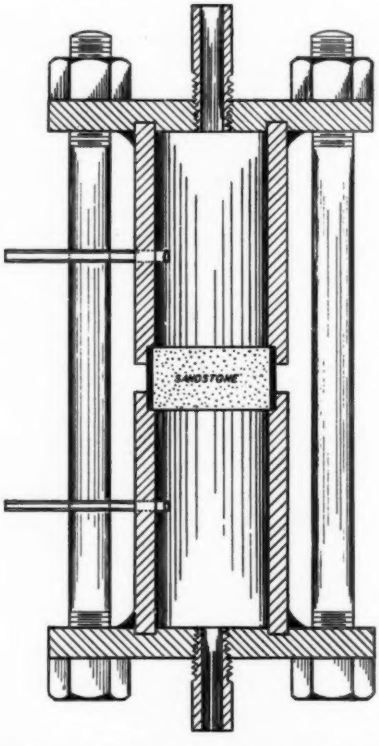


FIG. 2.—Cross section of sample holder showing method of mounting sample. Small shoulder against which sample rests is for purpose of relieving cement of excessive long-continued stress. Effective diameter of sample is taken as actual diameter of sample, the error introduced by decreased area at face being negligible. This error may be eliminated by replacing continuous shoulder by small lugs. For low pressure runs of short duration, shoulder or lugs may be completely eliminated.

cement around the seal will suffice to prevent excessive leakage due to an imperfect pressed-fit. The difficulty of removing all traces of oil is an argument for the use of relatively thin samples, as 1 cm. in length.

### MOUNTING OF SAMPLES IN FLOW TUBE

While there are many ways in which the sample may be satisfactorily mounted in the flow tube using sealing material or soft rubber gaskets, the arrangement shown schematically in Figure 2 is not only simple and easy to apply but has certain operating advantages.

The periphery of the dried and slightly heated sample is first coated with hot pitch or tar so as to cover this surface with an impermeable layer of the sealing material. It is then inserted in the ends of the tube, the through-bolts tightened slightly, and just sufficient heat applied to form a good bond. It will be noted that the tubes do not meet at the center, but a gap is left, the purpose of which is to permit detection of an imperfect seal which might otherwise permit by-passing around the sample. Throughout all of the mounting operation, care is taken to prevent any sealing material from covering the faces of the sample. With reasonable care, the coating is easily applied up to the end of the sample without appreciable encroachment upon the face. The pitch or tar is quite satisfactory for measurements with air or water since it is somewhat less brittle than other sealing materials. If oil or other fluids are used which dissolve the pitch even very slightly, it must be replaced by an insoluble material. Ordinary sealing wax is commonly used and has been found satisfactory for carbon tetrachloride and oil tests.

### ARRANGEMENT OF APPARATUS

The arrangement of the apparatus, the parts of which are made entirely of brass, is of course a matter of personal preference, provided, however, that certain details are not overlooked. The arrangement which has been found satisfactory is shown in Figure 3.

The sample holder is shown at *A*. *B* is a calcium chloride drying tube; *C* the wet test gas meter; *D* is the differential manometer reading the pressure drop across the sample; *E*, the manometer giving the pressure at the outflow end of the sample; *F* are reservoirs for use when permeability is measured with liquids; and *G* are test gauges for determining roughly the pressures existing in the reservoirs.

Attention is called to the use of manometers for pressure measurements rather than the use of gauges, which at best are not sufficiently accurate. Water manometers are used when the pressures involved are low and are replaced by mercury manometers for higher pressures. Obviously, the manometers must be so arranged that no fluid heads of unobservable amount can exist in the leads to the manometer, and for this reason when flowing liquids, the pressure

measurement may be obtained by the use of single columns of the fluid used in the test and directly connected to the pressure outlets of the sample holder with the zero pressure points properly referred to the zero-flow levels in the columns. As has already been pointed out, absolute pressures are required in gas flow measurements to reduce

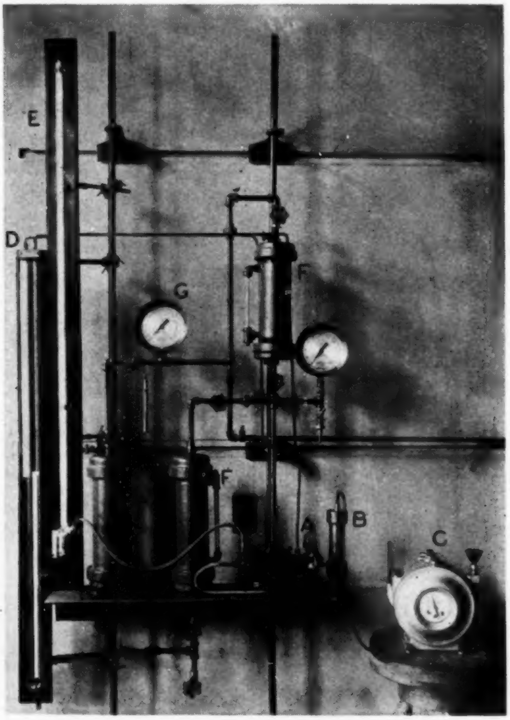


FIG. 3.—Complete apparatus for making permeability measurements.

the flow rates to the mean pressures; hence, a single manometer, measuring the pressure differential across the sample, is inadequate.

Another precaution, easily overlooked but a source of serious error, involves the mounting of the sample holder. For measurements with liquids, the sample holder should be mounted vertically with the input end at the bottom. In this manner, the top surface of the sample is always covered by liquid, and any possibility of an air film forming over the outlet face of the sample is completely eliminated. Capillary

forces at the outlet face may be of considerable magnitude if imperfect wetting exists at this face.

#### DETERMINATION OF RATE OF FLOW

There is, of course, no particular difficulty involved in measuring the volume of flow by the use of ordinary graduates and a stop watch. The only precaution required is the maintenance of steady pressure differentials during this operation. In the case of gas flow at slow rates, the output may be collected in the usual manner over water, taking due care that the final measured volume is the volume at known atmospheric pressure. For flow rates too high for such measurements, an accurately calibrated meter or gasometer of large capacity is satisfactory.

#### PREPARATION OF LIQUIDS USED IN MEASUREMENTS

A common source of error and one frequently overlooked is the cause of the slow plugging of the core sample as the liquid flows through it. This has been shown to be due, in the case of water, to dissolved silicic acid from the glass in which the water is usually handled, and, in the case of oil, to gummy substances formed by the oxidation of unsaturated hydrocarbons. To eliminate this trouble alone requires considerable manipulation since the water must be prefiltered through a sandstone or alundum filter immediately before using, or if oil is used, unsaturates must be removed by well-known chemical means, and the oil must be kept in a non-oxidizing atmosphere of nitrogen or natural gas. By observing proper precautions in preparing and handling the liquids, it is possible to maintain flow over long periods without appreciable plugging effects due to the liquid itself. In addition to plugging by solid materials in the liquid, a decreasing permeability may be observed if the fluids used contain dissolved air or gas. Such effects are eliminated by use of prefiltered, distilled water.

#### PROCEDURE IN MAKING LIQUID MEASUREMENTS

The sample having been properly prepared, dried, and mounted, it is not sufficient simply to apply a suitable pressure differential and note the rate of flow. Previous to the injection of water or other liquid, the sample contains air, and simply flowing the liquid through without further preparation may result in the trapping of air in some of the capillary interstices with a consequent decrease in the area available to the liquid flow. Application of high pressure gradients might suffice gradually to flush out or dissolve such gas masses, but a safer procedure is to exhaust the system by means of a vacuum pump attached to the output end. When the pressure in the flow sys-

tem has been reduced to a low value, the valve leading to the liquid source may be opened and the system allowed to fill. In this manner the danger of trapping gas masses within the sample is minimized, although not always entirely eliminated.

A further difficulty encountered when using water as a medium is the fact that the cementing material may be sufficiently soluble to allow some of the finer grains to be loosened and thus plug the core and reduce the apparent permeability of the sample. In fact, samples

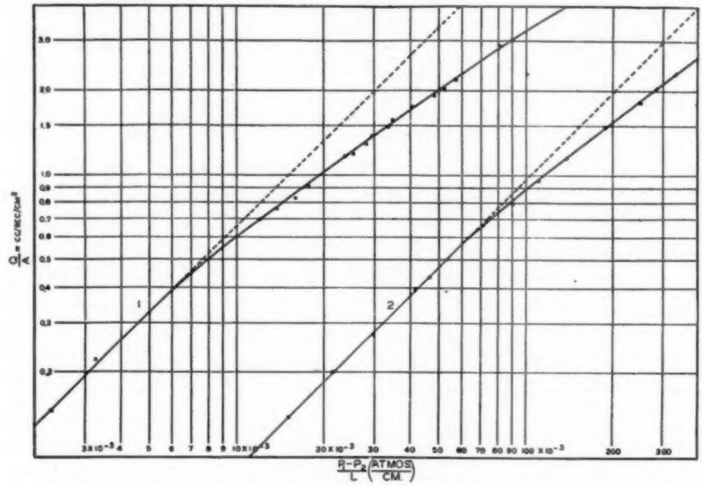


FIG. 4.—Liquid permeability data on two cores showing departure from viscous flow. Curve 1, Filtros disc grade R. Curve 2, Filtros disc grade H.

are occasionally encountered which completely disintegrate in contact with water. Carbon tetrachloride or other liquids of known viscosity may be used for such samples.

Having observed the precautions already outlined, the procedure is simply to apply a pressure differential across the sample and hold it at a constant value while the rate of flow is measured. The flow rate should be checked by several observations and averaged. It is also desirable to repeat the measurement at several values of pressure differential. The results obtained then permit a plot of flow rate *versus* pressure differential which should result in a straight line plot; the slope of which will give a good average for use in the permeability calculation. The use of such a plot also eliminates any question as to whether the flow is in the viscous or turbulent region.

A record of the temperature of the liquid should be made during the test in order that the viscosity of the fluid at the time of test may be determined. Very often the magnitude of the variation of liquid viscosity with temperature is not appreciated. The viscosity of water, for example, varies 2 per cent per degree Centigrade, and since the permeability varies inversely with viscosity, the permeability correction amounts to 2 per cent per degree Centigrade.

From the data obtained in the above observations, the permeability constant $k$ is calculated using equation 2. In order to make the procedure clear, the experimental data on two porous discs are given in Figure 4. In these tests far more data were taken than are necessary for an ordinary permeability determination, the observations having been deliberately extended into the range which shows departure from viscous flow. When the rate of flow *versus* pressure differential is plotted on log-log paper, the viscous region is indicated by that portion of the curve having a 45° slope, and as the degree of turbulence increases, the slope decreases until in the limit of complete turbulence, the slope of the curve would be 26° 34′, corresponding with a proportionality between the pressure gradients and the *squares* of the velocity.

From the 45° portion of curve 1 (Fig. 4), we may select the coördinates of some point such as: 0.4 cc./sec./cm.$^2$, $(P_1-P_2)/L=6.2\times 10^{-3}$ atmos./cm. Substituting in equation 3, noting that $A=1$ cm.$^2$ and the viscosity of water at 24° is 0.92 centipoise, we obtain

$$k = \frac{0.4 \times 0.92}{6.2 \times 10^{-3}} = 59.3 \text{ darcys.}$$

In a similar manner from curve 2 for the other sample,

$$k = \frac{0.6 \times 0.92}{0.064} = 8.62 \text{ darcys.}$$

The same result would be obtained by plotting the data on ordinary coördinate paper and observing that the viscous flow region is indicated by the linear portion of the curve. However, examination of the curves of Figure 4 brings out the point mentioned in the introduction, that high pressure gradients are necessary in the case of liquids to produce an appreciable departure from viscous flow. While the gradients required to show turbulence in the case of the two previous samples are not excessive, it is to be noted that their permeabilities are very high compared with those of the sands usually encountered in oil reservoirs, and a comparison of the two curves

shows that the departure from viscous flow in the $k=8.62$ sample occurred at a gradient 12 times higher than in the case of the $k=59.3$ sample. One would therefore reasonably conclude that in a sample of much lower permeability, viscous flow would obtain up to relatively high pressure gradients, and that only in the *immediate* vicinity of a well flowing at high rates would liquids depart seriously from viscous flow. This is of importance in considering field measurements which will be discussed in a later section.

### PROCEDURE IN MAKING GAS MEASUREMENTS

The procedure already described in preparation and mounting of the sample also applies to gas measurements. In addition, certain other precautions are necessary. Analogous to the care required in eliminating gas from the sample prior to flowing liquids is, in the case of gas flow, the necessity of removing any liquid normally retained in the pores. This is usually done by long careful drying in a suitable oven, or even by application of vacuum to aid in volatilizing the liquid. Furthermore, in order to prevent contamination with moisture during flow, as well as to be certain of the viscosity of the gas which varies with moisture content, the gas should first be passed through a suitable drying agent. Thus, in the case of air, which is the most convenient gas to use, it is passed through a calcium chloride drying tube before reaching the sample. Further, a similar tube is placed in series with each water manometer so that this water-saturated air can not reach the sample. At the same time such filters effectively remove dust and other solids which may exist in the air. While it may seem that these extreme precautions are unnecessary, it is the only way to eliminate error from these causes which at times may be serious.

As has already been mentioned, the manometers used in the gas flow tests must be such as to read absolute pressure, that is, a single differential manometer reading the pressure drop across the sample is wholly inadequate. This is due to the fact already discussed, that the rate of flow of gas is proportional to the difference in the squares of the input and exit pressures, and the pressures must therefore be in absolute units. Separate water or mercury manometers should be used to measure the pressure on each side of the sample or a differential manometer across the sample must be supplemented by an additional manometer at the outflow face of the sample. To these readings is added the barometric pressure to obtain absolute values.

The sample and the associated flow apparatus having thus been prepared, a suitable pressure gradient is applied and held constant while the rate of flow of the gas is measured. The gas may be collected

over water in the usual manner. For high rates of flow an accurate meter may be used. Several check readings should be taken in order to average out errors. Similar observations at several pressure differentials should be made, for by plotting the rate of flow at the mean pressure *versus* the difference between the absolute pressures, a good average value is obtained from the linear plot which should result. Further, by this means, as already pointed out, one may determine whether the permeability is being calculated in the viscous range as required.

In order to make the calculations clear, the following example is carried through from the original data obtained in the test to the final calculation for the permeability in darcys.

The data obtained in the test are shown in Table II and Table III.

Sample, 40–45-mesh sand; tube diameter, 2.16 cm.; area 3.66 cm.$^2$; length 29.9 cm.

TABLE II

| *Vol. of Air at Atmos. Press. (Cc.)* | *Time (Sec.)* | *Inflow Pressure (Cm. $H_2O$)* | *Outflow Pressure (Cm. $H_2O$)* | *Barometric Pressure (Cm. $H_2O$)* | *Temp. (°C.)* |
|---|---|---|---|---|---|
| 250 | 58.0 | 5.1 | 0 | 1,013 | 24 |
| 250 | 42.5 | 6.9 | 0 | 1,013 | 24 |
| 250 | 33.5 | 8.8 | 0 | 1,013 | 24 |
| 250 | 27.0 | 10.8 | 0 | 1,013 | 24 |
| 250 | 23.2 | 12.8 | 0 | 1,013 | 24 |
| 250 | 20.1 | 14.7 | 0 | 1,013 | 24 |

TABLE III

| *Cc./Sec./Cm.$^2$ at Atmos. Pressure* | *Inflow+ Bar. Press. (Cm. $H_2O$)* | *Outflow+ Bar. Press. (Cm. $H_2O$)* | $P_1$ *(Atmos.)* $\frac{\text{Col. 2}}{1{,}033}$ | $P_2$ *(Atmos.)* $\frac{\text{Col. 3}}{1{,}033}$ | $\frac{P_1+P_2}{2}$ | $\bar{Q}/A$ *(Cc./Sec./Cm.$^2$)* | $\frac{P_1-P_2}{L}$ |
|---|---|---|---|---|---|---|---|
| 1.18 | 1,018.1 | 1,013 | 0.9855 | 0.9806 | 0.9830 | 1.20 | $1.64\times10^{-4}$ |
| 1.61 | 1,019.9 | 1,013 | 0.9873 | 0.9806 | 0.9839 | 1.64 | $2.24\times10^{-4}$ |
| 2.04 | 1,021.8 | 1,013 | 0.9891 | 0.9806 | 0.9848 | 2.07 | $2.84\times10^{-4}$ |
| 2.53 | 1,023.8 | 1,013 | 0.9910 | 0.9806 | 0.9858 | 2.57 | $3.48\times10^{-4}$ |
| 2.94 | 1,025.8 | 1,013 | 0.9930 | 0.9806 | 0.9868 | 2.98 | $4.14\times10^{-4}$ |
| 3.40 | 1,027.7 | 1,013 | 0.9948 | 0.9806 | 0.9877 | 3.44 | $4.75\times10^{-4}$ |

In Figure 5 the data of column 7 (Table III) are plotted as ordinates against column 8 (Table III) as abscissae. The points lie on a straight line through the origin; hence, the flows are in the viscous region. The same data plotted on log-log paper give a straight line having a 45° slope.

As already pointed out, the slope of the curves, such as that in Figure 5, should give the permeability divided by the viscosity. In the present case, the slope is $7.29\times10^3$. Hence we have:

$$k = 7.29 \times 10^3\mu = 131.9 \text{ darcys.}$$

### GAS VERSUS LIQUIDS FOR MEASUREMENTS

Certain difficulties, encountered when using a liquid as the test fluid, may be eliminated by the use of gas. In addition to those already mentioned, in the case of very low permeabilities, the rate of flow of liquids is excessively slow even with undesirably high pressure gradients. In this case, not only is too much time required to attain a reasonable accuracy, but the importance of the disturbing factors already mentioned becomes very great. In order to eliminate some of the difficulties encountered when using liquids, it has been suggested that air or gas be used for all permeability measurements, since the

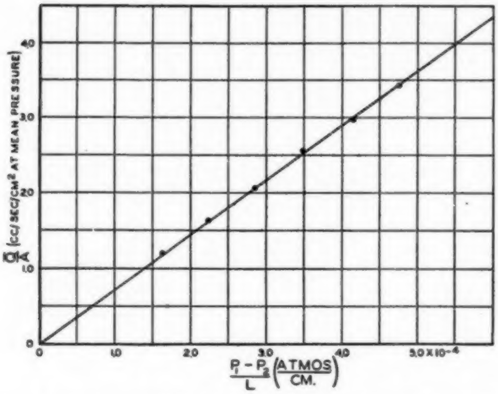


FIG. 5.—Gas permeability data on Berea sandstone. Diameter, 4.01 cm.; length, 1.86 cm.

results, if computed by equation 3, give the permeability valid for any fluid.

For some time past, considerable work has been done in this laboratory on the subject of correlation between gas and water permeability measurements. In fact, it is due to the attempts to obtain the exact correlation, involving only the relative viscosities of the fluids as theoretically required, that many of the details in technique were found necessary. The use of gas eliminates several of the sources of error inherent in the use of liquids which are difficult or even practically impossible to avoid completely.

Briefly summarized, the advantages of gas measurements are: (1) elimination of the necessity for taking the precautions required to prevent plugging of the sample due to materials carried by the liquids or to disintegration of the sample by loosening of the cementing ma-

terial; (2) elimination of the error due to air trapped within the sample and the need for evacuation and filling with liquid under a vacuum; and (3) a measurable flow is obtained even on "tight" samples without the use of excessive pressures.

These advantages are sufficient to present a clear case favoring the use of gas for permeability measurements, the results of which may be converted into values applying to any fluid of known viscosity. While the use of gas for this purpose is by no means new, it will be noted that in many of the discussions found in the literature, the results are in error due to the failure to recognize the difference in pressure relations between gas and liquid flow. The proper calculations have been given in the preceding sections.

In order to show that gas measurements actually give the same values of $k$ as liquid determinations, Table IV is presented, showing the results of both gas and liquid measurements on a few samples of unconsolidated and consolidated sands. The unconsolidated sands, which are the first two in the list, were packed in glass tubes 7 cm. long and 3.07 cm. in diameter. The poor check obtained on the 80–100-mesh sand was undoubtedly due to a slight change in packing when water was flowing together with incomplete removal of trapped air.

TABLE IV

| *Sample* | *Permeability (Darcys)* $k$ *(Air Measurements)* | $k$*(Liquid Measurements* |
|---|---|---|
| 40–45-mesh sand | 139.13 | 139.40 ($H_2O$) |
| 80–100-mesh sand | 24.90 | 22.00 ($H_2O$) |
| No. 1 sandstone (Woodbine) East Texas | 1.18 | 1.20 ($CCl_4$) |
| No. 2 sandstone (Woodbine) | 1.56 | 1.57 ($H_2O$) |
| No. 3 sandstone (Woodbine) | 1.63 | 1.63 ($H_2O$) |
| No. 4 sandstone (Berea) | 1.54 | 1.50 ($H_2O$) |

## PERMEABILITY MEASUREMENTS IN FIELD

Since the advent of bottom-hole pressure measurements in oil wells on a rather extensive scale, many applications of these data have been suggested. One of the most important applications and one used to some extent at the present time is the method of determining the potential production of a well from measurements of reservoir pressure together with bottom-hole pressures at various rates of flow. These data represent an effective-permeability measurement, and on this basis it has been suggested that the method be used to determine the relative permeabilities of the producing horizon surrounding the various wells in a field. It is to be noted, however, that the direct results represent only relative effective permeabilities, and since no specific dimensions are assigned, it is impossible to compare such

figures obtained in the field with measurements made on samples in the laboratory. Further, such measurements, expressed in terms of barrels/day/unit pressure differential, do not have the dimensions of permeability; hence, do not permit a comparison of sand permeabilities of one field with another since the dimensions of the well, penetration, sand thickness, et cetera, are not taken into account as they should be. To the writers' knowledge, a method of calculating permeabilities from well measurements has not previously been published.[5]

The previous paragraphs have presented suitable technique whereby accurate permeability measurements on core samples may be made in the laboratory. In common with similar measurements of porosity, the question invariably arises as to whether the results so obtained represent the effective permeability of the entire producing horizon, since complete cores are almost never available and the variations known to exist are often extremely large. Further, in the presence of fractures or other large voids, permeability measurements on small samples may result in very misleading conclusions as applied to the pay zone in bulk. Thus the voids in a cavernous limestone or any similar material may have dimensions comparable with the dimensions of the test pieces, and a measurement made on the small sample no longer represents the average flow through a very large aggregate of pore openings. In the formation itself, voids or fractures of relatively great dimensions may be present; in which case no measurement on samples will give the effective permeability of the pay zone.

For the aforementioned reasons, together with the fact that samples are often unobtainable, it is advantageous to make field measurements on the pay zone in place. For a maximum of usefulness, the effective permeabilities so obtained should be expressed in units which may be compared with laboratory measurements or with results in other fields. The following discussion on field permeability measurements is presented, therefore, with the purpose of outlining the procedure which may be used in reducing the field observations as nearly as possible to standard permeability units.

It is clear that certain approximations are necessary because of the fact that the geometry of the flow system must be assumed to be ideal. Thus in the case of laboratory measurements the flow system is known to be linear and no approximation is involved in applying the

[5] Since this paper was submitted a theory of permeability measurements in the field has been developed by Moore, Schilthuis and Hurst (Oil Weekly, May 22, 1933). Their theory, however, is based upon the short period transient and non-steady state flow about a well, whereas the results of this paper are to be applied only after the passage of these localized transients and the establishment of steady state flow conditions.

flow laws to linear systems as was done in deriving the equations of pp. 164–165. In the case of a well penetrating a sand, it is clear that the flow is essentially radial, and the flow laws are therefore applied, considering the flow to be of this nature. Thus the equations to be presented apply only to radial flow systems, but since the calculated permeability constant is an *effective* permeability, the assumption of radial flow really results in the reduction of the actual system to an equivalent radial system as a standard of comparison. This, as well as some other approximations, the nature of which will become evident, is implied when the term effective permeability is used. Attention may also be called to the fact that, since the flow laws for gas-liquid mixtures are not known, it is impossible, at this time, to present rigorous formulae applying to such mixtures, and an approximation on the gas-free liquid basis is necessary.

### CALCULATION OF PERMEABILITY FOR RADIAL FLOW SYSTEMS

As already stated, the equations which are given above have been derived by the application of known empirical flow laws for gases and liquids to the geometry of a radial system. Space does not permit the presentation of the derivations, but it may be stated that they are rigorous under steady state conditions, involving no empirical relations other than the fundamental flow laws which are based upon uncontroversial evidence.

From the equations for radial liquid and gas flow, it may be shown that the effective permeability may be expressed as:

$$k = \frac{\mu Q \log_e r_1/r_2}{2\pi t(P_1 - P_2)} \tag{4}$$

in the case of wells flowing gas-free liquids, and

$$k = \frac{\mu \overline{Q} \log_e r_1/r_2}{2\pi t(P_1 - P_2)} \tag{4a}$$

in the case of gas wells, where:

$k$ = permeability in darcys
$\mu$ = viscosity in centipoises
$t$ = thickness of sand, cm.
$r_1$ = reservoir radius, cm.
$r_2$ = well radius, cm.
$P_1$ = reservoir pressure at $r_1$ in atmospheres
$P_2$ = bottom-hole pressure at well in atmospheres

$Q$ = rate of flow, cc./sec. (for liquids)
$\overline{Q}$ = rate of flow, cc./sec. reduced to the mean pressure

$$\frac{P_1 + P_2}{2} \text{ (for gases)}$$

and where the wells are assumed completely to penetrate the pay zone.

The measurements which must be taken in the well are the closed-in bottom-hole pressure, which is essentially the effective reservoir

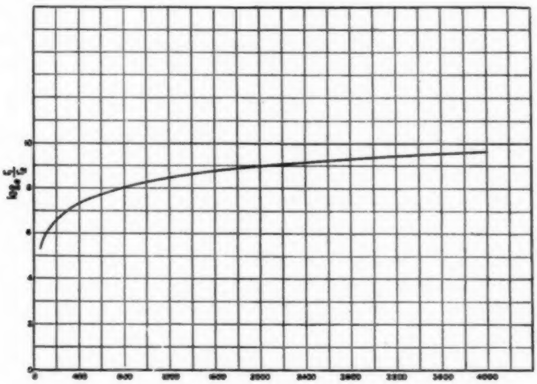

FIG. 6.—Effect of error in assumed radius of drainage when calcu'ating $k$, using well measurements.

pressure for the well, and the bottom-hole pressure at a known rate of flow. In addition, the radius $r_2$ of the bore hole, and the thickness $t$ of the *exposed* pay horizon must be known.

The most serious question which arises in attempting to assign numerical values to the factors in equations 4 and 4a is that of the reservoir radius $r_1$ with perhaps some uncertainty regarding the actual well radius in certain instances. Theoretically, the radius of drainage of *any* well, except for liquid flowing wells operating under artificial flooding methods, extends to the limits of the sand which it is draining, and thus it becomes impossible in practical cases to set a definite value for the reservoir radius. Furthermore, since each well is influenced by the interference effects from other wells draining the same sand, the value to be assigned to the radius $r_1$ appears to be even more indeterminate. However, it will be noted that the radii of both the well and the reservoir boundary enter as the $\log_e$ of their ratio, and

it is a property of this function that beyond a reasonable range of values of $r_1$ and $r_2$, which may be assumed, the $\log_e r_1/r_2$ changes only very slowly. Thus, in Figure 6 are plotted the values of $\log_e r_1/r_2$ where $r_2=0.25$ foot, while $r_1$ is varied from 50 to 4,000 feet. If the well radius is 0.25 foot and the assumed reservoir radius is 500 feet, the value of $\log_e r_1/r_2$ is 7.60 compared with a value of 8.29 for $r_1=1{,}000$ feet, or a resulting difference in the calculated value of $k$ of 9 per cent. Likewise, the difference between an assumption of $r_1=1{,}000$ feet and $r_1=2{,}000$ feet amounts to 8 per cent. Similarly, changing the well radius by a factor of 2 will result in equally small changes in the calculated value of $k$. Hence it is evident that, provided reasonably accurate figures for $r_2$ and a very rough assumption as to the numerical value of $r_1$ are used, the calculation will result in a value of $k$, expressed in standard units with an accuracy adequate for practical applications. The fact that a definite figure for $r_1$ is not obtainable in most cases will not introduce errors exceeding the normal errors involved in the other factors of the field measurement, and an accuracy of $\pm 10$ per cent may be expected if the pressure and fluid output measurements are reasonably accurate.[6] Experience derived from comparisons of well measurements and laboratory measurements will undoubtedly aid in selecting the most reliable figure for the reservoir radius. However, lacking the desired statistical data, a reasonable assumption is a radius $r_1=500$ feet, excepting in cases where a definite radius may be determined. Thus, if the test well is surrounded by offsets, *closed-in* pressure measurements in the offsets made simultaneously with the flow measurement in the test well, permit a definite assignment of the offset pressure $p_1$ at radius $r_1$ equal to the distance of the offset.

It may appear that the radial flow formula applies accurately only for strictly radial flow conditions. Analysis shows, however, that even if the pressures at a circular boundary are far from uniform, equations 4 and 4a are rigorous if the average pressure over the circular boundary is used. Likewise, it may be shown that if the well is not concentric with the assumed circular boundary, no appreciable error is introduced until the well location is within a very short distance of the boundary.

Attention is called to the implicit assumption in the case of equa-

[6] It will be noted in equations 4 and 4a or in any radial flow equation for steady states that if $r_1$ is assumed to be infinite, the productions $Q$ and $\overline{Q}$ will be zero at any finite value of pressure gradient and finite value of permeability. This apparently paradoxical result represents the true state of affairs and is quite analogous to the linear flow case wherein zero flow would be observed for any finite pressure difference imposed across the terminals of an infinite channel having a resistance greater than zero.

tion 4, that the fluid flowing in the sand is gas-free. While all wells flowing oil produce considerable quantities of gas, we are interested only in the volume of *free gas* present in the sand. Hence, if a well is flowing oil at a slow rate, involving high back pressures at the well face, the volume of free gas accompanying the oil through the sand will not be excessive excepting in the case of very gassy wells. For this reason the flowing pressure data are best taken at relatively low rates of flow in order to approach as nearly as possible the dead-liquid condition within the sand. Bearing in mind that equation 4 applies rigorously to artesian water flow or to oil production under conditions of hydraulic drive alone, proper judgment is necessary in applying it to wells under gas drive, particularly at high rates of flow.

While the precautions necessary to obtain accurate pressures are quite well known, it should be mentioned that not only must the well be closed in for a sufficient period of time to establish equilibrium between the well and the surrounding reservoir in order to obtain the reservoir pressure, but likewise in measuring the bottom-hole pressure at various rates of flow, a constant rate must be maintained for a sufficient period of time to enable a steady-state pressure distribution to build up around the well. Obviously, the tighter the sand, or the higher the rate of flow, the longer will be the transient period involved. Experience is required in order to judge the proper time interval necessary in avoiding observations during the transient state. In some wells having very permeable pay sands, 30 minutes to 1 hour may be sufficient while others will require many hours to establish essentially steady-state conditions.

The following data observed in an East Texas well will suffice to illustrate the method of calculation.

| *Bottom-Hole Pressure in Pounds* | *Rate of Flow* |
|---|---|
| 1,275 | 45 bbls./hr. |
| 1,450 | closed in 1 hr. |
| 1,470 | closed in 2 hr. |
| 1,470 | closed in 3.5 hr. |

Well diameter = 7 inches
Penetration = 5 feet

Reducing these data to C. G. S. units, with the exception of $r_1$ and $r_2$ (which enter the equation as a ratio and hence the units used are immaterial, provided both radii are expressed in the same units), we obtain as the essential data for equation 4:

$t = 5$ ft. $= 153$ cm.
$r_1 = 500$ ft. (assumed)
$r_2 = 0.3$ ft. (approximately)

$P_1 = 1{,}470$ lbs./in.$^2 = 100$ atmos.
$P_2 = 1{,}275$ lbs./in.$^2 = 87$ atmos.
$Q = 45$ bbls./hr. $= 1{,}980$ cc./sec.
$\mu = 2.3 \times .34 = 1.03$ centipoises at 60°C., assuming 10 per cent by volume of propane and butane.

Substituting in equation 4:

$$k = 1.03 \times \frac{1{,}980 \times \log_e \frac{500}{0.3}}{2\pi 153(100 - 87)}$$

$$= 1.03 \times \frac{1{,}980 \times 7.42}{6.28 \times 153 \times 13} = 1.21 \text{ darcys.}$$

It will be observed that only the actual thickness of sand exposed in the well has been used in the foregoing calculation. The fact that only the depth of penetration is involved in the calculation is not to be interpreted as meaning that the entire sand thickness is not being drained. Actually a correction factor should be applied which takes into account the total sand thickness. This correction is discussed later.

In the discussion of the calculation of permeability, it was shown that the permeability is a constant only for purely viscous flow and that any departure towards turbulent flow involves a change in $k$, and in the factor involving $P_1$ and $P_2$ of equation 2. This condition likewise applies to field measurements of permeability. Thus at very high rates of flow, when turbulence will develop, particularly in the immediate vicinity of the well, the observed effective permeability will decrease. Measurements should therefore be made at moderate production rates. Data from tests made at various rates of flow may be plotted as in the case of linear flow, described in detail in the paragraphs on calculation of permeability, and the curves of log $Q$ or log $\overline{Q}$ plotted against log $(P_1 - P_2)$ will give a linear 45° plot in the viscous flow region, gradually flattening out and approaching a 26.5° slope as the degree of turbulence increases.

### CALCULATION OF LIQUID PERMEABILITIES—GRAVITY RADIAL FLOW

While a measurement of permeability in wells flowing under gravity drive alone is of little interest to petroleum engineers, it is perhaps most important to hydrologists who are interested in ground water flow or ordinary water wells which have no artesian drive.

The flow system assumed is one in which a sand body with an impermeable base is partially or wholly filled with liquid and is com-

pletely penetrated by a well. If the water level in the well is lowered by pumping below its normal closed-in level, water will flow into the well under the action of gravity alone.

In order to obtain the effective permeability of the sand, the pump is stopped for a sufficient period of time to permit the water level to reach its normal height, and a measurement is made of this height calculated from the bottom of the sand. The well is next pumped at a known rate, and after sufficient time has elapsed to permit the water level in the well to reach its new steady-state position, the new height above the base of the sand is measured. Several such observations at different pumping rates will give independent calculations.

It has been shown, experimentally, that the permeability of the sand is expressed by:

$$k = \frac{\mu Q \log_e r_1/r_2}{\pi \gamma g(h_1^2 - h_2^2)} \qquad (5)^7$$

where:

$k$ = permeability, darcys
$r_1$ = reservoir radius, cm.
$r_2$ = well radius, cm.
$\gamma$ = density of liquid
$g$ = acceleration of gravity = 0.00097 atmos. for unity density
$h_1$ = fluid height in reservoir, cm. (closed-in height in well measured from bottom of the sand)
$h_2$ = fluid height in well, cm., measured from bottom of the sand
$\mu$ = viscosity of liquid in centipoises
$Q$ = fluid output cc./sec.

Again, if the radius $r_1$ is not accurately determinable, very little error will be involved if a radius of 500 feet is assumed.

It should be mentioned that this equation is strictly applicable only to the case of a homogeneous sand; that is, a sand in which the permeabilities in all directions are the same and in which no impermeable bedding planes exist within the sand body. If the producing horizon is made up of a number of thin zones separated by impermeable boundaries, each zone must be treated separately, since each will behave as an individual gravity flow system. Evidently, a complex producing horizon becomes difficult to handle, and only by

[7] This equation applies only when $h_1$ is equal to, or less than, the sand height.

a large number of observations on flow rate *versus* water level in the well may the problem be properly analysed.[8]

#### CALCULATION OF LIQUID PERMEABILITIES—COMPOSITE, ARTESIAN, AND GRAVITY RADIAL FLOW

It has also been shown that in case some artesian drive exists, that is, if $h_1$ exceeds the sand height, the permeability is given by:

$$k = \frac{\mu Q \log_e r_1/r_2}{\pi \gamma g(2h_s h_1 - h_s^2 - h_2^2)} \tag{6}$$

where:

$h_1$ = *total* fluid head in cm. measured from the bottom of the sand
$h_s$ = sand height, cm.
$h_2$ = fluid head in pumping well, measured from bottom of sand, cm. Other notations as in equation 5.

It will be noted that, as required, this equation reduces to the pure radial flow, equation 4, when $h_2$ is equal to the sand height.

Again, equation 6 is applicable only to a homogeneous sand, and a horizon made up of individual zones separated by impermeable boundaries requires individual treatment of the several zones.

#### CORRECTIONS FOR PARTIALLY PENETRATING WELLS

In equations 4 and 4a, the thickness of sand, $t$, exposed by the well bore has been used rather than the total thickness of the producing horizon. It has been shown by lengthy analytical work, that in the case of wells penetrating a considerable part of the total pay horizon, the major contribution to the total flow is the radial component which alone is considered in equations 4 and 4a. In addition to the radial flow, however, is a contribution arising from flow in the unexposed sand below the bottom of the well. When the well penetration is small, this contribution to the flow becomes important. It may be taken into account approximately by a simple correction to be applied to the value of $k$ as obtained from the aforementioned equations.

In Figure 7 is plotted the correction factor $C$ *versus* well penetration, in which the well penetration is expressed as the ratio in per cent

[8] It may be of interest to note that field measurements for determining the permeability, in the case of water wells, has already been suggested in the literature. However, the methods proposed have involved the observation of the fluid height and fluid-height gradient in a well near the one that is being pumped for two pumping rates, or the gradients or fluid heights in two wells forming a line with the pumping well for a single pumping rate. In either case, the measurements are evidently more difficult and costly than those proposed here.

of the exposed sand thickness to the total sand thickness of the pay horizon. Thus by multiplying the $k$ obtained from the application of equation 4 by the correction factor $C$, as read from Figure 7, the proper value of $k$ is obtained.

The correction obtained from Figure 7 is that for liquid flow in an isotropic sand. If the permeability across the bedding plane is less than that along the bedding plane, the flow in the unexposed region below the well is decreased. If some idea as to the relative perme-

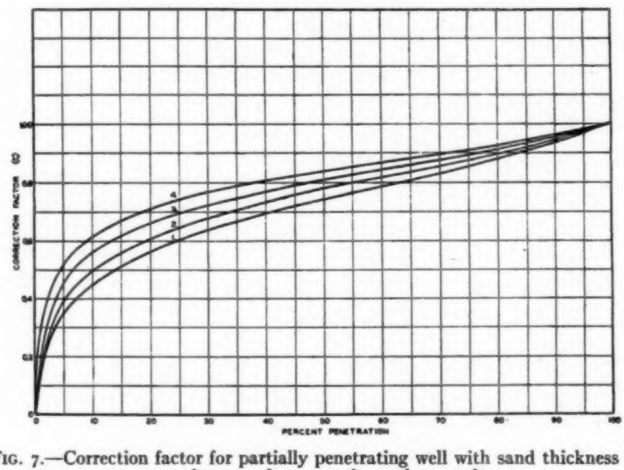

FIG. 7.—Correction factor for partially penetrating well with sand thickness of: *1*, 50 ft.; *2*, 75 ft.; *3*, 125 ft.; and *4*, 200 ft.

abilities in the two directions is known, the following procedure may be used approximately to take this anisotropy into account.

Let the ratio of permeability perpendicular to the bedding plane to that parallel to the bedding plane be $\alpha$. Then the new correction factor, $C_\alpha$, to be used as a multiplier instead of $C$, as read from Figure 7, is

$$C_\alpha = \frac{C}{C + \alpha - \alpha C} \cdot \tag{7}$$

It is apparent that if $\alpha = 1$, corresponding with a homogeneous sand, $C_\alpha = C$. If the permeability across the bedding plane is zero, $\alpha$ becomes zero and $C_\alpha = 1$, meaning that no flow occurs in the unpenetrated sand, the flow being strictly radial, and no correction is applied to equation 4.

It is of interest to mention that for gas flow the partially penetrating well correction is the same as that for liquid flow. Hence, in the case of gas wells partially penetrating the pay horizon, the procedure is the same as in the foregoing paragraph, excepting that obviously equation 4a is used to determine the uncorrected $k$.

## SUMMARY

A technique for laboratory measurements of the permeability of porous materials has been described which is both convenient and accurate. The proper formulae used in calculating the permeability from the experimental data, using either liquids or gas, are given. The writers make no claim to the originality of all of the various details presented, but rather it is their hope that the discussion regarding the technique of permeability measurements represents a fair summary of the essential precautions required in order to obtain accurate experimental results. They do, however, feel that the treatment of both gas and liquid permeability calculations on a common basis, involving only a generalized interpretation of Darcy's law as given in the present discussion, has heretofore not been sufficiently stressed.

The section on permeability measurements in the field presents formulae whereby the effective permeability, obtained from well measurements, may be expressed in proper units for purposes of comparison with laboratory measurements or those in other fields. Careful study will show other useful applications of these fundamental equations.

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BULLETIN OF THE AMERICAN ASSOCIATION OF PETROLEUM GEOLOGISTS
VOL. 18, NO. 2 (FEBRUARY, 1934), PP. 191-211, 9 FIGS.

# PHYSICAL CHARACTERISTICS OF BRADFORD SAND, BRADFORD FIELD, PENNSYLVANIA, AND RELATION TO PRODUCTION OF OIL[1]

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## ABSTRACT

The Bradford district of northwestern Pennsylvania and adjacent portions of New York has produced 302,800,000 barrels of oil during the period from 1871 to 1932, inclusive. Almost all of this production has come from a single horizon, the Bradford sand, which has been proved productive in a continuous area of 84,000 acres. This gives the Bradford pool a major rank among the great oil pools of the United States both from the standpoint of total production and of total continuous productive area. It is the remarkable success that has been attained in the application of artificially conducted water drives as a means of increasing the extraction of oil from a pool that had reached the economic limit by ordinary production methods, however, that has attracted attention to the field in recent years. It is quite probable that the total production will be increased to 500 million barrels by this means within the next 15 or 20 years.

Several factors have contributed to the success attained by water flooding. Due to the relatively low permeability of the sand and an original reservoir pressure that was probably subnormal, an unusually large percentage of the oil still remained in the sand after the economic limit had been reached by ordinary production methods. Although wide variations in total thickness and number and thickness of shale breaks occur in the sand body, in large parts of the field the individual sand layers themselves show a remarkable degree of uniformity in texture, porosity, and oil content. In those parts of the field where the greatest difficulty has been encountered in the application of the water drive, core studies have shown that alternate layers of sand are present that vary appreciably from one another in texture, porosity, and permeability. The relatively shallow depth at which the sand occurs and the superior quality of the oil are also important factors that have made water flooding, as practiced in the Bradford district, economically feasible.

The Bradford oil field of northwestern Pennsylvania and adjacent portions of New York, which has already produced 302,800,000 barrels during the period from 1871 to 1932, inclusive, a figure which will probably be raised to 475–500 million barrels in the future by the methods of production now in use, has attracted worldwide attention in recent years on account of the remarkable success that has been attained in the application of artificially conducted water drives as a means of increasing the extraction of oil from a pool that had reached the economic limit by ordinary production methods. Almost all of the Bradford production has come from a single horizon, the Bradford Third sand, which has been proved productive in a continuous area of

[1] Published by permission of the State Geologist of Pennsylvania.

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84,000 acres, giving the Bradford pool not only a major rank among the great oil pools of the United States from the standpoint of total production[3] but also placing it in second position with respect to total continuous productive area.

### STRATIGRAPHIC POSITION

The Bradford First and Second sands are of only minor importance as sources of oil in the Bradford district. The Third sand is, therefore, referred to simply as the Bradford when the productive horizon of the field is meant.

That the Bradford sand was deposited under marine conditions is indicated by the fact that marine fossils are very sparingly distributed throughout the main body of sand in many parts of the field. Fragments of carbonized plant remains are also present. Although these are presumably of land origin, their fragmentary nature indicates that they were transported to their present environment by stream and wave currents. Just above the sand, in places separated from it by a few inches of shale, usually there is one thin bed, or more, of fine-grained gray calcareous sandstone which contains an abundance of marine shells.

Subsurface studies recently made by the writer across northern Pennsylvania and southern New York indicate that the Bradford Third sand lies near the middle of the Chemung group and is of upper Devonian age.[4]

### SUBSURFACE STRUCTURE

The major subsurface structural features of the Bradford sand in the Bradford district consist of two asymmetrical anticlines trending northeast and southwest, plunging southwest, and converging on the northeast in a broad dome.[5] The closure on this dome within the productive limits of the Bradford pool is approximately 100 feet. The anticlines are characterized by broad tops with gentle dips toward the northwest and considerably steeper dips toward the southeast.

The major structural axes, together with the 50-foot structure contours showing the elevation of the top of the Bradford sand, are shown in Figure 1. The boundaries of the Bradford pool and several

[3] James McIntyre, "Record of the Leading Producing Fields of the United States," *The Oil and Gas Journal* (March 24, 1932), p. 11.

[4] Charles R. Fettke, "Subsurface Devonian and Silurian Sections across Northern Pennsylvania and Southern New York," *Bull. Geol. Soc. Amer.*, Vol. 44 (1933), pp. 601–60.

[5] J. B. Newby, P. D. Torrey, C. R. Fettke, and L. S. Panyity, "Bradford Oil Field, McKean County, Pennsylvania, and Cattaraugus County, New York," *Structure of Typical American Oil Fields*, Vol. 2 (Amer. Assoc. Petrol. Geol., 1929), p. 420.

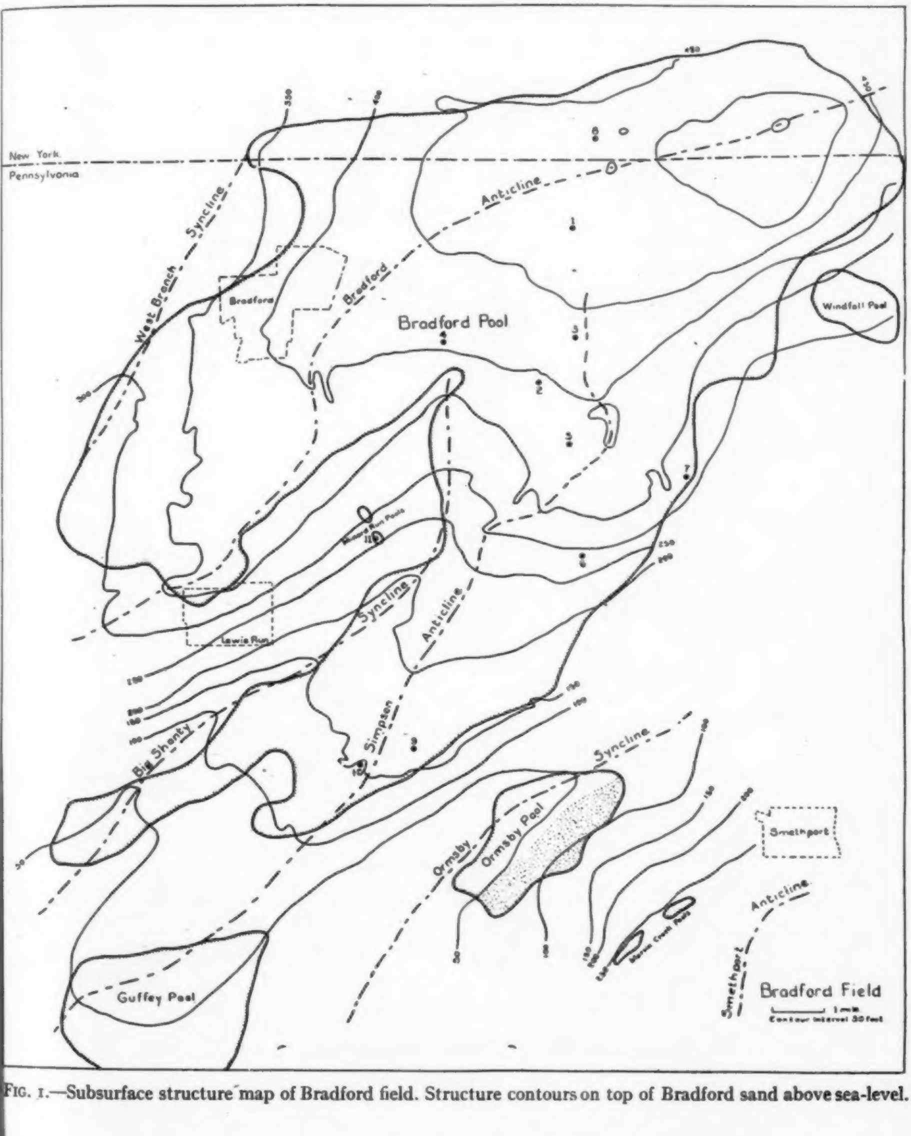


FIG. 1.—Subsurface structure map of Bradford field. Structure contours on top of Bradford sand above sea-level.

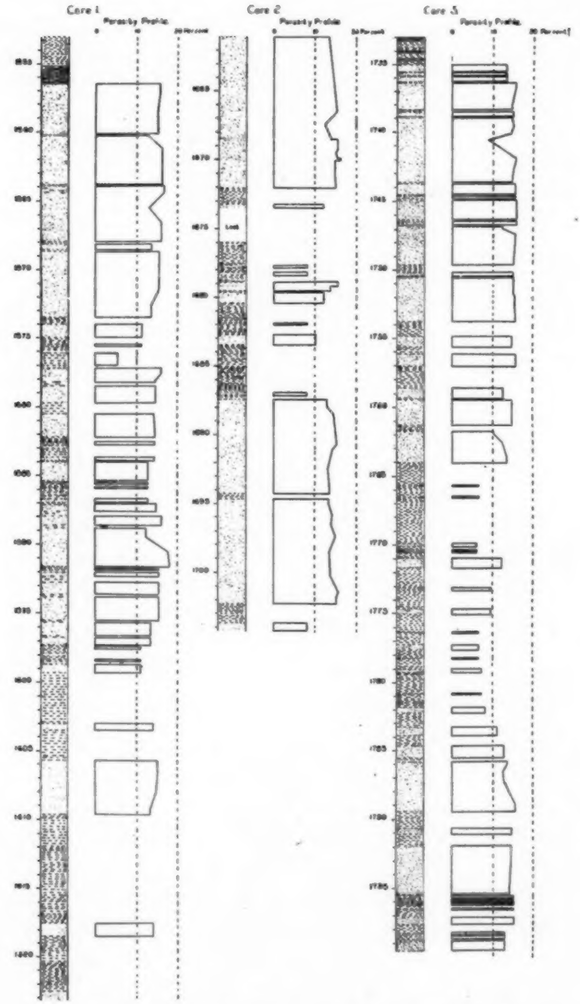

FIG. 2.—Sections and porosity profiles of Cores 1, 2, and 3

smaller pools which produce from the Bradford horizon are shown on this map.

The major structural axes of the region parallel the Appalachian folds and are no doubt of tectonic origin. More detailed study reveals many minor configurations on the upper surface of the sand which are

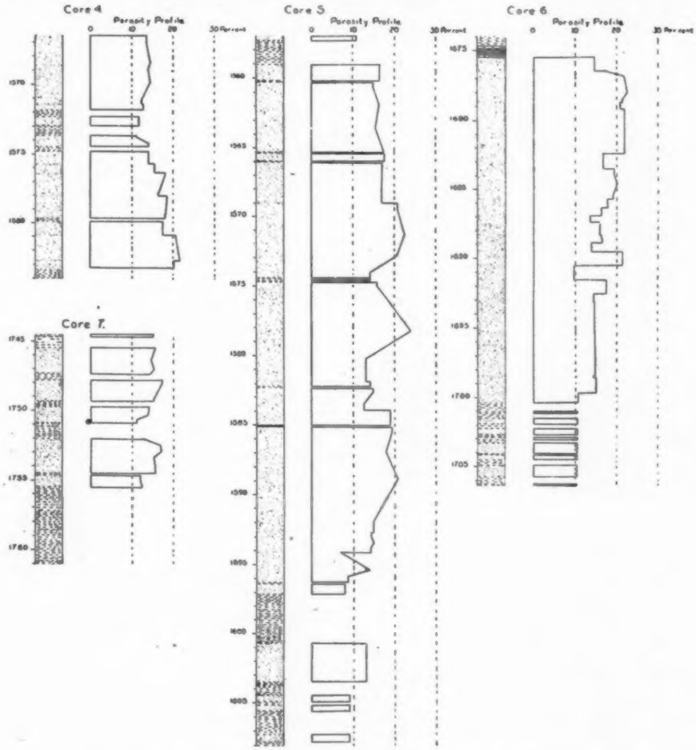


FIG. 3.—Sections and porosity profiles of Cores 4, 5, 6, and 7.

due apparently to depositional conditions and differential compaction.

### CHARACTERISTICS OF SAND

The Bradford sand, although exhibiting a remarkable continuity and a considerable degree of homogeneity over 84,000 acres of proved territory, is by no means uniform in the entire area of the field. Wide variations in total thickness and number and thickness of shale part-

ings occur in many places between adjacent properties and even adjacent wells. Cross-bedding could not be recognized in cores. Studies of cores indicate variations in porosity, uniformity and actual

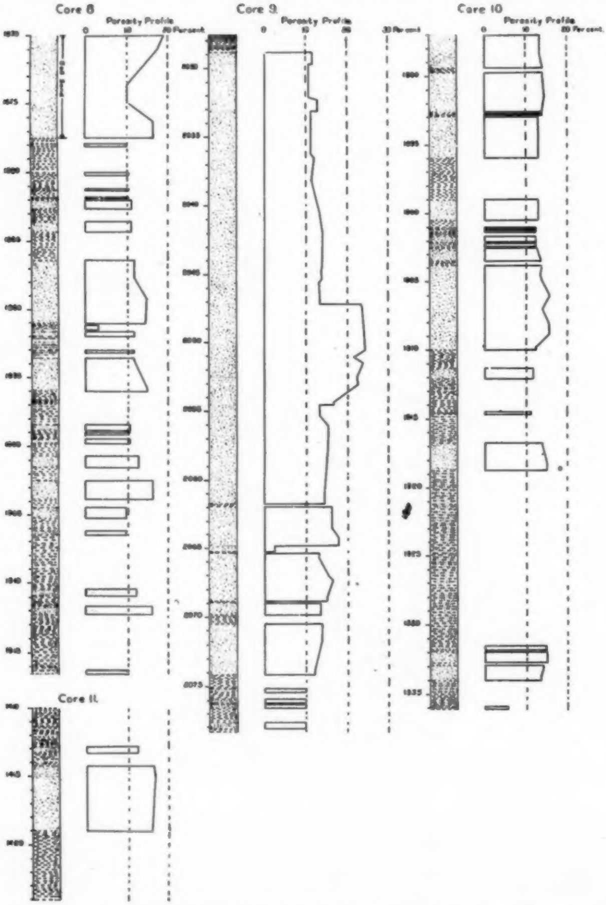


FIG. 4.—Sections and porosity profiles of Cores 8, 9, 10, and 11.

size of grains, and character and amount of cementing material, both vertically and laterally, in the sand. In general, however, these variations are not as great as in some of the other oil sands of the Appalachian fields studied in detail by the writer.[8]

Detailed sections of the Bradford sand from 11 wells, widely scattered in the Bradford field, are shown graphically by the usual conventional symbols in Figures 2, 3, and 4. Their location is indicated on the map of Figure 1. These sections illustrate the wide variations, not only in total thickness of the sand body, but also in the number and thickness of the shale partings which occur in the sand. The data are summarized in Table 1.

TABLE I

TOTAL THICKNESS OF BRADFORD SAND AND THICKNESS AND PER CENT OF OIL-BEARING SANDSTONE, AS SHOWN BY ELEVEN REPRESENTATIVE CORES

| *Core Number* | *Total Thickness of Bradford Sand—Feet* | *Thickness of Oil-Bearing Sandstone—Feet* | *Per Cent of Total Thickness Consisting of Oil-Bearing Sandstone* |
|---|---|---|---|
| 1 | 66.67 | 40.84 | 61 |
| 2 | 43.26 | 27.59 | 64 |
| 3 | 64.58 | 39.42 | 61 |
| 4 | 16.87 | 15.16 | 90 |
| 5 | 50.76 | 42.42 | 84 |
| 6 | 30.85 | 28.11 | 91 |
| 7 | 11.01 | 8.00 | 73 |
| 8 | 46.50 | 23.00* | 49 |
| 9 | 49.26 | 43.81 | 89 |
| 10 | 49.09 | 23.69 | 48 |
| 11 | 6.20 | 5.30 | 85 |

* 7.50 feet of this consist of gas-bearing sandstone.

## MINERALOGICAL COMPOSITION

The Bradford sand is chocolate-brown sandstone composed predominantly of fine to very fine angular quartz grains. In thin section, the sandstone presents an interlocking mosaic of fine angular quartz grains, as shown in the microphotographs of Figures 5 and 6. Figure 5 represents a section cut parallel with the bedding and Figure 6, perpendicular to it. A few flakes of muscovite and biotite and an occasional plagioclase grain are present in nearly all thin sections. Some of the mica flakes have been bent around the quartz grains. A small amount of interstitial material, consisting of an aggregate of sericite and a brown mica-like and other clay material, occurs between the quartz grains, but it is not uniformly distributed. Silica, as a secondary crystalline outgrowth from the original quartz grains and the small amounts of clay material mentioned form the bond. Calcite

[6] C. R. Fettke, "Core Studies of the Second Sand of the Venango Group from Oil City, Pennsylvania," *Petroleum Development and Technology in 1926* (Amer. Inst. Min. Met. Eng., 1927), p. 219.

———, "Ten Years' Application of Compressed Air at Hamilton Corners, Pennsylvania, with Core Studies of the Producing Sand," *Petroleum Development and Technology in 1927* (Amer. Inst. Min. Met. Eng., 1928), p. 303.

is rarely present in large enough amounts to constitute an important bonding agent. In most thin sections, only one grain or two can be seen. Occasional small clusters of minute pyrite crystals, clearly of secondary origin, are present. In sections cut perpendicular to the bedding, stratification is frequently faintly indicated by the alignment of the occasional mica flakes and some of the elongated quartz grains parallel to the bedding planes.

Microscopic examination has revealed that the low porosities of the sandstone layers may be due to three causes: (1) larger amounts of

Fig. 5.—Microphotograph of typical section of Bradford sand cut parallel with bedding. Taken with crossed nicols.

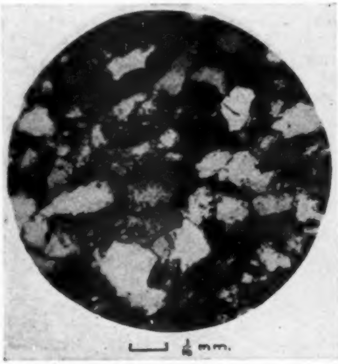

Fig. 6.—Microphotograph of typical section of Bradford sand cut perpendicular to bedding. Taken with crossed nicols.

interstitial clay minerals; (2) greater percentages of silica deposited as secondary crystalline outgrowth from the original quartz grains and as cryptocrystalline silica; and (3) large amounts of calcite or related carbonates between the quartz grains.

### CHEMICAL COMPOSITION

A chemical analysis of the sandstone occurring at a depth of 1,741.92 feet in Core No. 3 was made according to the methods recommended by Washington.[7] The sample was crushed to pass through a 100-mesh sieve, then extracted with carbon tetrachloride followed by petroleum ether, and dried at 130°C. The results are shown in Table II.

Organic carbon was determined in a combustion furnace. The presence of 0.3 per cent organic carbon indicates that not all the

[7] H. S. Washington, *Chemical Analysis of Rocks*. 2d edition, 1910.

TABLE II

CHEMICAL ANALYSIS OF BRADFORD SANDSTONE
(From a depth of 1,741.92 feet in Core No. 3)

| | *Per Cent* |
|---|---|
| $SiO_2$ | 86.89 |
| $Al_2O_3$ | 6.95 |
| $Fe_2O_3$ (including $FeO$) | 2.55 |
| $MgO$ | 0.42 |
| $CaO$ | 0.07 |
| Alkalies | Not determined |
| $H_2O$ (combined) | 0.89 |
| $CO_2$ | Trace |
| $C$ (organic) | 0.30 |

petroleum residues were removed by the extraction with carbon tetrachloride and petroleum ether. The sand sample was carefully examined for carbonized plant remains before it was crushed, and none were found.

### SIZE AND SHAPE OF GRAINS

Screen analyses of representative samples from different horizons in Cores 3, 6, 8, and 9 are given in Tables III, IV, V, and VI. In the entire Bradford field, the Bradford sand consists of fine-to-very fine grains. In considerable areas the different layers that make up the sand body show remarkable uniformity in grain size, similar to that exhibited by Core No. 3; even in Core 8, which shows the greatest range, the variations between the different layers are not large.

A comparison of porosity with grain size indicates that the percentage of fine material, that is, grains that pass through a 325-mesh sieve, is one of the determining factors in the porosity of the sand. The lower this percentage, the higher the porosity, since the fine particles fill the voids between the larger particles and thus reduce porosity. In general, in the Bradford sand, the layers with high porosities (more than 20 per cent) consist of coarser grains than the others. The higher porosity is apparently due to the fact that the sands were sorted better during deposition and less silt was deposited with them.

The grains of the Bradford sand are predominantly angular. In a typical sample about 78 per cent were classed as angular, 12 per cent subangular, 7 per cent fairly well rounded, and 3 per cent rounded. Part of this angularity may be due to secondary silica deposited as a secondary crystalline outgrowth from the original quartz grains after the sand was laid down.

### POROSITY

The porosity determinations which furnished the data for the construction of the porosity profiles, shown in Figures 2, 3, and 4, were

TABLE III

SCREEN ANALYSIS OF EIGHT SAMPLES OF BRADFORD SAND FROM CORE NO. 3

| Size of Openings Millimeters Through | Caught on | Depth 1,736.71 Feet Per Cent | Depth 1,737.92 Feet Per Cent | Depth 1,741.92 Feet Per Cent | Depth 1,749.21 Feet Per Cent | Depth 1,751.88 Feet Per Cent | Depth 1,759.04 Feet Per Cent | Depth 1,770.04 Feet Per Cent | Depth 1,788.92 Feet Per Cent |
|---|---|---|---|---|---|---|---|---|---|
| .295 | .208 | 0.1 | 0.0 | 0.6 | 0.5 | 0.0 | 0.1 | 0.0 | 0.0 |
| .208 | .147 | 4.8 | 4.4 | 2.9 | 14.4 | 3.3 | 6.4 | 4.0 | 8.7 |
| .147 | .104 | 30.2 | 27.4 | 25.3 | 36.3 | 31.1 | 29.1 | 24.6 | 33.9 |
| .104 | .074 | 37.5 | 29.4 | 33.4 | 30.2 | 31.0 | 29.9 | 22.3 | 26.1 |
| .074 | .061 | 6.3 | 16.1 | 16.1 | 4.4 | 16.6 | 6.4 | 14.9 | 11.2 |
| .061 | .043 | 8.7 | 9.8 | 9.9 | 5.9 | 8.5 | 11.3 | 13.6 | 9.3 |
| .043 | | 12.4 | 12.8 | 12.7 | 8.2 | 9.5 | 16.8 | 20.5 | 10.9 |
| Average grain size* millimeters | | .094 | .090 | .090 | .109 | .092 | .092 | .084 | .099 |
| Porosity per cent | | 15.8 | 14.8 | 15.7 | 15.2 | 15.5 | 12.5 | 6.0 | 15.3 |

* The average grain size shown in Tables III–VI was determined from the screen analyses by the method described by H. Ries and J. A. Rosen, "Foundry Sands," *Michigan Geol. Survey Ann. Rept.* (1907), p. 50.

TABLE IV

SCREEN ANALYSES OF NINE SAMPLES OF BRADFORD SAND FROM CORE NO. 6

| Size of Openings Millimeters Through | Caught on | Depth 1,677.98 Feet Per Cent | Depth 1,678.50 Feet Per Cent | Depth 1,679.75 Feet Per Cent | Depth 1,682.96 Feet Per Cent | Depth 1,684.58 Feet Per Cent | Depth 1,690.00 Feet Per Cent | Depth 1,692.88 Feet Per Cent | Depth 1,699.13 Feet Per Cent | Depth 1,700.00 Feet Per Cent |
|---|---|---|---|---|---|---|---|---|---|---|
| .589 | .417 | 0.0 | 0.2 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| .417 | .295 | 0.0 | 1.1 | 0.0 | 0.1 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| .295 | .208 | 1.3 | 4.5 | 0.0 | 1.8 | 0.7 | 0.0 | 0.2 | 0.0 | 0.1 |
| .208 | .147 | 29.9 | 17.2 | 15.9 | 15.5 | 11.2 | 13.9 | 4.1 | 2.7 | 2.7 |
| .147 | .104 | 39.9 | 34.5 | 45.2 | 34.7 | 41.7 | 53.1 | 31.5 | 32.5 | 31.2 |
| .104 | .074 | 16.6 | 24.8 | 20.3 | 25.7 | 30.5 | 17.0 | 34.4 | 31.9 | 36.2 |
| .074 | .061 | 4.4 | 3.8 | 5.9 | 4.9 | 4.3 | 4.4 | 6.8 | 13.7 | 6.5 |
| .061 | .043 | 3.8 | 4.4 | 4.6 | 5.6 | 4.0 | 5.3 | 8.6 | 9.4 | 9.0 |
| .043 | | 3.9 | 9.5 | 8.1 | 11.7 | 7.5 | 6.5 | 14.3 | 9.7 | 14.3 |
| Average grain size millimeters | | .128 | .121 | .113 | .106 | .110 | .115 | .093 | .093 | .092 |
| Porosity per cent | | 22.7 | 21.6 | 21.8 | 16.8 | 20.2 | 21.6 | 14.5 | 15.1 | 10.8 |

TABLE V

SCREEN ANALYSES OF SIX SAMPLES OF BRADFORD SAND FROM CORE NO. 8

TABLE V

SCREEN ANALYSES OF SIX SAMPLES OF BRADFORD SAND FROM CORE NO. 8

| Size of Openings Millimeters Through | Caught on | Depth 1,871.00 Feet Per Cent | Depth 1,876.25 Feet Per Cent | Depth 1,887.70 Feet Per Cent | Depth 1,890.80 Feet Per Cent | Depth 1,895.80 Feet Per Cent | Depth 1,911.97 Feet Per Cent |
|---|---|---|---|---|---|---|---|
| 1.651 | 1.168 | 0.0 | 0.2 | 0.0 | 0.0 | 0.0 | 0.0 |
| 1.168 | .833 | 0.2 | 0.7 | 0.0 | 0.0 | 0.0 | 0.0 |
| .833 | .589 | 0.1 | 0.2 | 0.0 | 0.0 | 0.0 | 0.0 |
| .589 | .417 | 0.7 | 0.6 | 0.0 | 0.0 | 0.1 | 0.0 |
| .417 | .295 | 2.4 | 2.4 | 0.1 | 0.1 | 0.5 | 0.0 |
| .295 | .208 | 12.2 | 11.5 | 3.7 | 9.0 | 5.0 | 2.0 |
| .208 | .147 | 35.1 | 36.6 | 23.0 | 27.6 | 36.2 | 20.7 |
| .147 | .104 | 29.2 | 27.6 | 30.8 | 34.1 | 33.7 | 36.6 |
| .104 | .074 | 10.3 | 8.7 | 19.3 | 14.7 | 12.8 | 22.2 |
| .074 | .061 | 1.5 | 1.9 | 4.4 | 2.3 | 2.2 | 4.5 |
| .061 | .043 | 3.3 | 3.5 | 5.7 | 4.5 | 3.2 | 6.1 |
| .043 | | 5.1 | 6.1 | 13.0 | 7.6 | 6.3 | 7.8 |
| Average grain size millimeters | | .159 | .165 | .118 | .135 | .139 | .117 |
| Porosity per cent | | 17.7 | 16.5 | 12.1 | 14.7 | 15.0 | 16.1 |

TABLE VI

SCREEN ANALYSES OF EIGHT SAMPLES OF BRADFORD SAND FROM CORE NO. 9

| Size of Openings Millimeters Through | Caught on | Depth 2,040.59 Feet Per Cent | Depth 2,047.13 Feet Per Cent | Depth 2,051.07 Feet Per Cent | Depth 2,053.07 Feet Per Cent | Depth 2,054.57 Feet Per Cent | Depth 2,058.07 Feet Per Cent | Depth 2,063.56 Feet Per Cent | Depth 2,067.04 Feet Per Cent |
|---|---|---|---|---|---|---|---|---|---|
| .589 | .417 | 0.0 | 0.0 | 0.0 | 0.1 | 0.0 | 0.1 | 0.0 | 0.0 |
| .417 | .295 | 0.0 | 0.1 | 0.0 | 0.5 | 0.1 | 0.1 | 0.0 | 0.0 |
| .295 | .208 | 0.1 | 1.9 | 0.9 | 7.7 | 3.9 | 3.5 | 0.1 | 3.2 |
| .208 | .147 | 5.5 | 35.9 | 30.5 | 50.3 | 19.5 | 24.7 | 12.0 | 13.8 |
| .147 | .104 | 36.1 | 45.6 | 47.1 | 30.1 | 31.1 | 35.4 | 43.8 | 26.5 |
| .104 | .074 | 35.4 | 10.2 | 14.1 | 6.3 | 24.9 | 20.3 | 29.2 | 32.1 |
| .074 | .061 | 5.2 | 1.2 | 1.3 | .8 | 4.5 | 3.3 | 3.2 | 6.4 |
| .061 | .043 | 7.3 | 1.8 | 2.0 | 1.5 | 6.0 | 5.6 | 4.8 | 7.0 |
| .043 | | 10.4 | 3.1 | 3.9 | 2.6 | 9.8 | 7.1 | 6.7 | 10.9 |
| Average grain size millimeters | | .099 | .139 | .132 | .157 | .117 | .125 | .110 | .107 |
| Porosity per cent | | 13.4 | 23.3 | 21.7 | 22.7 | 16.8 | 15.1 | 16.2 | 15.5 |

made according to the method described by Melcher.[8] The thickness of oil-bearing sand present in each core and its average porosity and, where the sand body can be divided into several distinct parts, similar data for each part, are given in Table VII.

TABLE VII

AVERAGE POROSITIES OF BRADFORD SAND FROM ELEVEN CORES

| Core Number | Thickness of Oil-Bearing Sand Present Feet | | Average Porosity Per Cent | |
|---|---|---|---|---|
| 1. Entire sand body | 40.84 | | 14.6 | |
| 2. Entire sand body | 27.59 | | 14.1 | |
| Top "pay" | | 11.08 | | 14.2 |
| Shale parting | | 2.00 | | 11.7 |
| Bottom "pay" | | 14.51 | | 14.4 |
| 3. Entire sand body | 39.42 | | 13.8 | |
| Top "pay" | | 25.58 | | 14.4 |
| Shale parting | | 2.67 | | 9.0 |
| Bottom "pay" | | 11.17 | | 13.7 |
| 4. Entire sand body | 15.16 | | 15.9 | |
| 5. Entire sand body | 42.42 | | 16.6 | |
| 6. Entire sand body | 28.11 | | 16.4 | |
| 7. Entire sand body | 8.00 | | 14.9 | |
| 8. Entire sand body | 23.00 | | 13.4 | |
| Gas "pay" | | 7.50* | | 14.4 |
| Oil "pay" | | 15.50 | | 12.9 |
| 9. Entire sand body | 43.81 | | 15.4 | |
| Upper portion | | 18.26 | | 12.7 |
| Middle portion ("loose streak") | | 7.44 | | 23.3 |
| Lower portion | | 18.11 | | 14.9 |
| 10. Entire sand body | 23.69 | | 13.7 | |
| 11. Entire sand body | 5.30 | | 16.0 | |

* Gas-bearing sand.

Figure 2 reveals a considerable degree of uniformity in the porosities of individual layers of sandstone. This is a desirable characteristic in connection with flooding operations. The wells from which the three cores were taken are located in a portion of the Bradford field in which some of the most successful water drives have been conducted.

The eleven cores described, as well as a considerable number of others from various parts of the Bradford field, do not indicate any relationship between porosity and the major structural features. Exceptionally porous layers of sandstone, "loose streaks," occur more

[8] A. F. Melcher, "Determination of Pore Space of Oil and Gas Sands," *Trans. Amer. Inst. Min. Met. Eng.*, Vol. 65 (1921), p. 469.

commonly in the eastern of the two lobes of the southern part of the field than in the western or the northern part of the field.

Some idea of the nature of the pores in the Bradford sand can be obtained from the microphotographs shown in Figures 7 and 8, representing polished surfaces by reflected light. The light areas show the mineral grains, while the black ones represent the pores. Figure 7 represents a surface parallel with the bedding and Figure 8, one perpendicular to it. The bedding is clearly shown in the latter by the alignment of the grains. The sample has a porosity of 15.7 per cent.

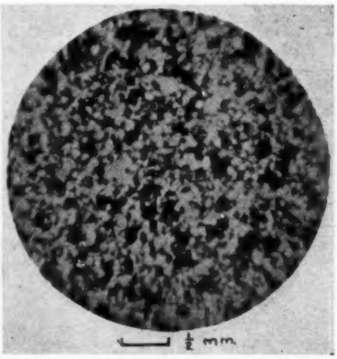

FIG. 7.—Microphotograph of polished surface of Bradford sand cut parallel with bedding.

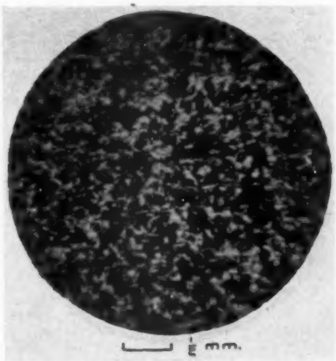

FIG. 8.—Microphotograph of polished surface of Bradford sand cut perpendicular to bedding.

## PERMEABILITY

The permeability of an oil or gas sand is its capacity for transmitting fluids, either liquids or gases, under pressure. This property of the sand is of particular importance in connection with increasing the recovery of petroleum by water flooding or repressuring with air or gas, inasmuch as on it, to a considerable extent, depends whether or not rejuvenation methods are economically feasible in a particular pool, what pressures are necessary, and what is the best well spacing to use.

The permeability of a sand depends on the size and shape of the openings and the extent to which these communicate with one another, as well as the ratio of their volume to the total volume of the sand.

Actual grain size, degree of uniformity of grain size, shape of grains, manner of packing of grains, and amount of cementing ma-

terial between the grains are all factors that determine the relative permeabilities of different layers of the sand. All, with the exception of the first, have an important bearing on the porosity and are to a considerable extent reflected in it. Hence actual grain size and porosity are usually excellent criteria for judging the relative permeabilities of different layers of sand. Permeability and porosity, however, are not synonymous terms and should not be used interchangeably. Porosity simply indicates the percentage of void space present in the sand that is available for the occupancy of either liquids or gases. It

TABLE VIII

RESULTS OF PERMEABILITY TESTS WITH WATER PARALLEL WITH BEDDING ON FIFTEEN SAMPLES OF BRADFORD SAND

| *Core No.* | *Depth of Sample Feet* | *Aver. Grain Size Mm.* | *Poros. Per Cent* | *Permeability** *Exper.* | *Permeability** *Calcul.* | *Per Cent of Calculated Permeability Represented by the Experimental* |
|---|---|---|---|---|---|---|
| 3 | 1,736.71 | .094 | 15.8 | .0082 | .0038 | 216 |
| 3 | 1,749.21 | .109 | 15.2 | .0037 | .0031 | 119 |
| 3 | 1,759.04 | .092 | 12.5 | .0005 | .0010 | 50 |
| 6 | 1,677.98 | .128 | 22.7 | .0366 | .0298 | 123 |
| 6 | 1,678.50 | .121 | 21.6 | .0213 | .0225 | 95 |
| 6 | 1,682.96 | .106 | 16.8 | .0039 | .0054 | 72 |
| 6 | 1,684.58 | .110 | 20.2 | .0139 | .0154 | 90 |
| 6 | 1,692.88 | .093 | 14.5 | .0034 | .0024 | 142 |
| 6 | 1,700.00 | .092 | 10.8 | .0005 | .0004 | 125 |
| 8 | 1,876.25 | .165 | 16.5 | .0264 | — | — |
| 8 | 1,890.80 | .135 | 14.7 | .0026 | .0026 | 100 |
| 8 | 1,895.80 | .139 | 15.0 | .0017 | .0029 | 59 |
| 9 | 2,040.59 | .099 | 13.4 | .0012 | .0015 | 80 |
| 9 | 2,051.07 | .132 | 21.7 | .0323 | .0231 | 140 |
| 9 | 2,063.56 | .110 | 16.2 | .0039 | .0044 | 89 |

* The permeability is represented by the volume of water in cubic centimeters which will pass through a length of sand of 1 centimeter with a cross-sectional area of 1 square centimeter in 1 second when the pressure-drop through the sand is 1 atmosphere. The experimental permeability has been obtained from the amount of water which passed through a 0.5 inch cube during the first 15 minutes under a pressure-drop of 75 pounds per square inch at room temperature. The calculated permeability has been obtained from the empirical equation derived by plotting the experimental permeabilities against porosities on log-log coördinates.

does not give a picture of the pore pattern, namely, the size of the openings, their shape, and the extent to which they are connected, all of which influence the permeability.

Possible cross-bedding, lensing, and variations in grain size and porosity parallel with, as well as perpendicular to, the bedding in different layers of the sand must not be overlooked in connection with the consideration of the permeability of the sand body in place.

Another condition that may affect the ease with which water or any other driving medium can be forced through different layers of

the sand depends on whether or not the entire pore space is filled either with liquid or with gas, or whether liquid and gas are both present as alternating globules and bubbles and, if so, their relative proportions. The viscosity of the oil is another factor. The relative permeability of a certain layer of sand as determined in the laboratory, therefore, may not necessarily be a true criterion of the way in which that particular layer will behave under the conditions in the sand body.

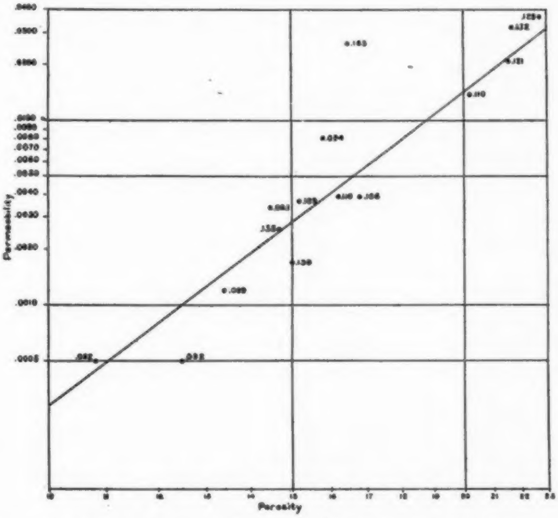


FIG. 9.—Relation of permeability to porosity in Bradford sand. Figures after points represent average grain size in millimeters.

The results of permeability tests on 15 samples of Bradford sand representative of different layers from four of the cores described are shown in Table VIII. The apparatus employed and the method of procedure used in making these tests have been described in previous articles.[9]

The relationship of permeability to porosity is shown by the graph of Figure 9 which has been plotted on log-log coördinates. The straight line was located by the method of averages. The point representing the sample occurring at a depth of 1,876.25 feet in Core No. 8 with an

[9] C. R. Fettke and R. D. Mayne, "Permeability Studies of Bradford Sand," *Nat. Petrol. News*, Vol. 22 (July 23, 1930), p. 61.
C. R. Fettke and W. A. Copeland, "Permeability Studies of Pennsylvania Oil Sands," *Trans. Amer. Inst. Min. Eng.*, Vol. 92, p. 329.

average grain size of 0.165 millimeter and a porosity of 16.5 per cent, was not taken into consideration in locating this line, inasmuch as it is somewhat coarser than most Bradford sand and does not come from the oil-bearing part of the sand, but from a gas pay which overlies it in this part of the field. Its permeability is considerably greater than that of a typical Bradford sand of the same porosity. The 14 typical samples of Bradford oil-bearing sand show that the differences in their average grain sizes are not sufficient to be an important factor in greatly disturbing the relationship between permeability and porosity. In general, one would expect the sands with the coarser grains to fall above the line and those with the finer below, but, as shown by the graph, there are several notable exceptions to this rule.

In terms of the units employed, the relationship between permeability and porosity for Bradford sand can be expressed as follows.

$$K = 6.49 \times 10^{-10} P^{5.65}.$$

### OIL CONTENT OF SAND

Samples for the determination of oil content were obtained from Cores 3 and 9. The sand in Core No. 3 (Fig. 2), can be conveniently divided into three parts, namely, a top "pay," a shale parting, and a bottom "pay." The top "pay" contains 25.58 feet of sandstone with an average porosity of 14.4 per cent; the shale parting, only 2.67 feet with an average porosity of 9.0 per cent; and the bottom "pay," 11.17 feet with an average porosity of 13.7 per cent. Four samples from the upper "pay" showed an average oil content of 46.5 per cent by volume of the total pore space, while three from the lower "pay" showed 40 per cent. On the basis of these tests, the top "pay" contains 12,865 barrels of oil per acre and the bottom "pay" contains 4,800—a total of 17,665 barrels.

In Core 9, the sand was found to consist of three parts (Fig. 4): an upper portion, 18.26 feet thick with an average porosity of 12.7 per cent; a middle portion, "loose streak," 7.44 feet thick with an average porosity of 23.3 per cent; and a lower portion containing 18.11 feet of sand with an average porosity of 14.9 per cent. Three samples tested from the upper portion possessed an average oil content of 43 per cent by volume of the total pore space; one sample from the middle portion, 39 per cent; and two samples from the lower portion, an average of 50 per cent. On the basis of these tests, there are present 7,700 barrels of oil per acre in the upper, 5,200 barrels in the middle, and 10,500 barrels in the lower portion—a total of 23,400 barrels for the entire sand body.

Cores 3 and 9 came from areas in which the economic limit by the ordinary methods of production had practically been reached, but in which the water drive had not yet been applied. The oil content of the samples was determined by the method already described in previous articles.[10]

The results obtained from such tests unfortunately give only an approximate idea of the actual oil content of the sand in the ground. They give a minimum figure and the actual oil content may be considerably greater. Some oil is lost in the coring operation. Some evaporation losses also take place while the samples are in storage and there is a slight unavoidable loss after they are removed from the containers and crushed preparatory to testing.

Although the core tests give only minimum figures, in estimating oil reserves, the writer is firmly convinced from numerous core analyses checked against actual production figures, that there is no justification for the assumption that the entire pore space of oil sands in the Appalachian fields was necessarily occupied by oil originally, and that by deducting the quantity of oil already recovered from a particular tract, the remaining supply can be estimated from the total pore space available in the sand. In the case of Core No. 3, for example, there is a sufficient volume of pore space present to have contained 39,638 barrels per acre. The natural production from this area did not exceed 5,000 barrels per acre, leaving 34,638 barrels still to be accounted for if 100 per cent saturation is assumed. The core tests show only 17,655 barrels or approximately half the indicated oil content. It is hardly conceivable that this difference can be accounted for by shrinkage in volume due to loss of gas originally held in solution and losses incurred in the coring operation and the testing of the samples.

## CONDITIONS OF SEDIMENTATION

In the Bradford district, the area of thick sand development at the Bradford horizon coincides very closely with the outlines of the pool as shown in Figure 1. Along the margins, the shale layers interbedded with the sandstone increase in thickness and the sandstone layers become thinner and fewer. Farther from the pool, only one or two comparatively thin lenses of sand are recognized at the Bradford horizon and, in some places, the development of sand is so insignificant that

[10] C. R. Fettke, "Core Studies of the Second Sand of the Venango Group from Oil City, Pennsylvania," *Petroleum Development and Technology in 1926* (Amer. Inst. Min. Eng., 1927), p. 229.

———, "Core Studies of Oil and Gas Sands with Particular Reference to the Eastern Fields," *Amer. Petrol. Inst., Div. Prod. Rept. 826–3R* (June, 1930), p. 28.

its presence is not recognized by the driller, and other sandstones above or below it are mistaken for it.

A very similar condition exists in the non-productive area between the western and eastern lobes of the pool. This is illustrated by Core 11, taken from a well located in one of two small isolated pools in this area which have yielded only a small production. No cores are shown for the western lobe, but the sand over much of it has a total thickness and other characteristics that are comparable with the northern part and the eastern lobe.

In several localities, particularly in the eastern lobe, but not restricted entirely to it, there are elongate bodies of thick sand containing few or almost no shale partings, on the sides of which the sand thins rapidly and has numerous shale layers interfingering with it. Some of the larger of these may be as much as 8,000 feet or more in length and only 1,200 or 1,500 feet wide. Core No. 9 comes from such an area. Most of them are much smaller and the ratio of their lengths to their widths is greater. In many places, the trends of the longer axes of these sand bodies are roughly parallel with the long axes of the lobes. The sand encountered in them is slightly coarser than that on either side and possesses a higher porosity.

The foregoing features and the outlines of the pool suggest a deltaic origin. At the time that the Bradford sand was deposited, a stream with a very gentle gradient entered an arm of the Chemung sea from the northeast and spread its sediments in the form of a delta over the region. Two main distributaries caused the thick sand development along the two lobes. The location of the parallel and branching channels along these distributaries and the shifts which occurred in them from time to time account for the wide and rapid variations in the thickness of the sand and the number and thickness of the shale beds which interfinger with it.

## RELATION OF OIL ACCUMULATION TO PHYSICAL CHARACTERISTICS AND STRUCTURE

In the accumulation of the Bradford oil pool, the presence of an unusually thick sand at the Bradford horizon, coinciding with the outlines of the pool, was a factor of major importance, although no doubt the structural features (Fig. 1) also were important factors in the migration of the oil to its present position.

Over a considerable portion of the dome in the northeastern portion of the field, the upper 35–40 feet of the Bradford sand originally contained considerable volumes of gas and little or no oil. The sand in much of this area has a total thickness of 90 feet. Another similar

gas area was found underneath the structural nose just east of the well from which Core No. 5 was taken. Here the upper 20–25 feet of sand were gas-bearing, the total thickness ranging from 45 to 70 feet.

The limits of the pool, as has already been stated, were controlled more by sand conditions than by the structure. At the extreme northeast edge, production terminates at the 450-foot contour, while at the extreme southwestern tip of the eastern lobe, the top of the sand has an elevation of only 40 feet above sea-level.

In the western lobe, production on the northwest extends to the axis of the West Branch syncline, but on the southeast, it does not extend very far beyond the axis of the Bradford anticline. Similarly, production along the eastern lobe extends to the axis of the Big Shanty syncline on the northwest but terminates at a considerable elevation above the axis of the Ormsby syncline on the southeast.

With the exception of wells located near the edges of the pool, little or no salt water was encountered in the Bradford sand in the productive territory. There is, however, a fairly definite oil-salt water contact along the western, southern, and southeastern margins of the pool, but this does not occur at any definite elevation. No edge-water encroachment has been noted as the oil has been withdrawn from the pool, although in a well drilled in 1926, a short distance beyond the southwestern limits of the eastern lobe, salt water was encountered in the Bradford sand under sufficient head to rise 1,200 feet in the hole. The sand here has a thickness of only 14 feet. A well drilled along the Simpson anticline just north of the Guffey pool also encountered salt water.

In the non-productive area located on the southeastern flank of the Bradford anticline, where some of the steepest dips in the field occur, between the two lobes of the Bradford pool, considerable salt water is produced with a little oil from the two little pools, shown in Figure 1. The sand here is thin, as shown by Core No. 11. Numerous wells have been drilled through the Bradford sand at the southern edge of the Borough of Lewis Run to a sand about 100 feet below the Bradford, from which some oil production has been obtained. In many wells, salt water and only a showing of oil were encountered in a thin sand interstratified with numerous shale layers occurring at the Bradford horizon.

The anomalous occurrence of salt water around the margins of the pool may possibly be due in part to regional tilting of the area toward the southwest since the time of oil accumulation. An alternate explanation is that the numerous sand lenses of the Bradford sand are not continuous; hence, no perfect alignment of the edge water at a

definite level around the margins of the pool is possible. If this is the case, however, the question naturally arises: to what extent can lateral migration in the Bradford sand itself be called upon to account for the accumulation of the vast volume of oil present in the Bradford pool?

The locations of the smaller pools east, southeast, and south of the Bradford (Fig. 1) are primarily controlled by the presence of local lenses of sand at the Bradford horizon. In the Ormsby pool, oil occurs in that portion along and immediately adjacent to the axis of the Ormsby syncline, and gas occurs in that portion extending up onto the flank of the Smethport anticline. Most of the production from this pool comes from a deeper sand, but only that portion which is productive in the Bradford sand is shown on the map.

### RELATION OF PRODUCTION OF OIL TO PHYSICAL CHARACTERISTICS

Data on the initial production of individual wells and yields per acre by ordinary production methods for individual properties are hard to secure. Since 1875, when original development on an extensive scale started, most properties have changed ownership several times and most of this information has been lost. The average natural production per acre for the entire pool probably did not exceed 3,000 barrels per acre.

Where the information is available, however, a close relationship between the physical characteristics of the sand, particularly the porosity and thickness of oil-bearing "pay," and the production data is revealed. On a property of 22.5 acres, developed by 6 wells, adjacent to the one from which Core No. 1 was taken, the natural production averaged 5,500 barrels per acre. The thickness of oil-bearing sand on this property ranged from 21 to 26 feet as compared with 34 to 41 feet on the one from which Core No. 1 came, but the porosity of the sand and other characteristics are the same.

On a property of 1,225 acres, originally developed by 180 wells, in the southern part of the field from which Cores Nos. 9 and 10 came, the natural production averaged 2,900 barrels per acre. An elongate body of thick sand containing a so-called "loose streak" occupies about one-fourth of the tract. Core No. 9 is representative of this portion of the property, while Core No. 10 is more typical of the balance.

In the major portion of the Bradford pool, the initial production of the wells was comparatively small, being usually less than 50 barrels, and pumping had to be resorted to from the start. Flowing wells were encountered mostly in the eastern lobe of the field. Some flowing

wells had an initial production as high as 600 barrels and a few isolated wells even more. This is the area in which portions of the sand frequently show high porosities, 20 per cent or more, by volume, as is shown in Cores Nos. 5, 6, and 9. In most of the field porosities in excess of 16 per cent are rarely encountered. On a property adjacent to the one from which Core No. 6 was taken, some of the original wells had an initial production of as high as 350 barrels. Some large wells, up to 400 barrels, are near the well from which Core No. 9 came.

The relation of the two areas in which a gas "pay" was encountered above the oil "pay" to the structure has already been mentioned.

A close relationship exists between the physical properties of the sand and the success attained with water flooding. Cores Nos. 1, 2, and 3 come from an area in which some of the most successful floods have been in operation. The ideal sand for water flooding appears to be one which has practically all of its grains less than 0.2 millimeter in diameter with an average grain size of 0.1 millimeter and which has the porosity of its different members falling within the limits of 14 and 16 per cent.

Cores Nos. 2 and 3 were taken from wells drilled in connection with five-spot floods. The well from which Core No. 2 was taken produced 8,728 barrels of oil during the first 21 months. The area included between the 4 water-intake wells which surround it is 1.32 acres, giving an average recovery of 6,612 barrels per acre. At the end of the 21 months the well was producing 1 barrel of oil and 20 barrels of water per day. The well from which Core No. 3 was taken yielded 11,107 barrels of oil during a period of 5 years and at the end of that time was still producing 1.2 barrels of oil per day and 11 barrels of water. This well and a near-by old well located in the midst of a "five-spot,"[11] 1.94 acres in area, had produced at the end of that period an amount of oil equivalent to 6,390 barrels per acre.

One of the most difficult conditions to contend with in the application of the water drive in the Bradford field is the occurrence of alternate layers of sand that vary greatly from one another in porosity and hence in permeability. In two layers of typical Bradford sand having porosities of 15 and 20 per cent respectively, according to the experimental data, the latter will be five times as permeable as the former. An occurrence such as that shown in Core No. 9, where the upper 18.26 feet of sandstone has an average porosity of 12.7 per cent; the next 7.44 feet, 23.3 per cent; and the lower 18.11 feet, 14.9 per cent; can not be flooded efficiently as a unit. The water travels along the middle layers, leaving the others almost untouched.

[11] A "five spot" consists of 4 water intake wells at the corners of a square and a producing well in the center.

BULLETIN OF THE AMERICAN ASSOCIATION OF PETROLEUM GEOLOGISTS
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# TEXAS AND LOUISIANA SALT-DOME CAP-ROCK MINERALS[1]

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ABSTRACT

This paper is a catalogue of the minerals known to have been found associated with the salt domes of Texas and Louisiana. Twenty-eight minerals and varieties are listed. The paper is illustrated with ten plates of photographs. The genesis of the minerals is not discussed. A bibliography of 15 papers pertaining to salt dome minerals is given.

A number of articles have appeared in this *Bulletin* and a few in other scientific publications regarding the petrography of salt-dome cap rocks in general, describing the minerals found in one dome, or announcing the discovery of an individual mineral previously unrecognized. In this paper, the writers have tabulated all the solid minerals found to date in the cap rocks of Texas and Louisiana salt domes and have shown most of them in their different occurrences by photographs.

Generally, the cap rock is considered to be composed of anhydrite and gypsum and in some places calcitic rock, with or without sulphur. The writers believe that the majority of geologists are not aware of the great variety of minerals in salt-dome cap rock, and that is the sole reason for this presentation. They do not advance any theories regarding the formation or accumulation of the cap-rock series, the possibility of its altering from one mineral to another, the deposition of the numerous sulphate, carbonate, sulphide, chloride, and oxide minerals, or the formation of the enormous sulphur deposits in a few of the dome caps.

Accumulation of data on this subject is slow, and has resulted from the inspection of thousands of cores from hundreds of wells. Most of the specimens have been collected from two main sources, the extensive coring in connection with sulphur exploration and mining, and dumps of shafts sunk through cap rock for salt mining.

[1] Read before the Association at the Houston meeting, March 23, 1933. Manuscript received, October 12, 1933. Published with permission of the Gulf Production Company and the Texas Gulf Sulphur Company.

[2] Chief Paleontologist, Gulf Production Company.

[3] Mining engineer, Texas Gulf Sulphur Company.

TABLE I

Salt-Dome Cap-Rock Minerals

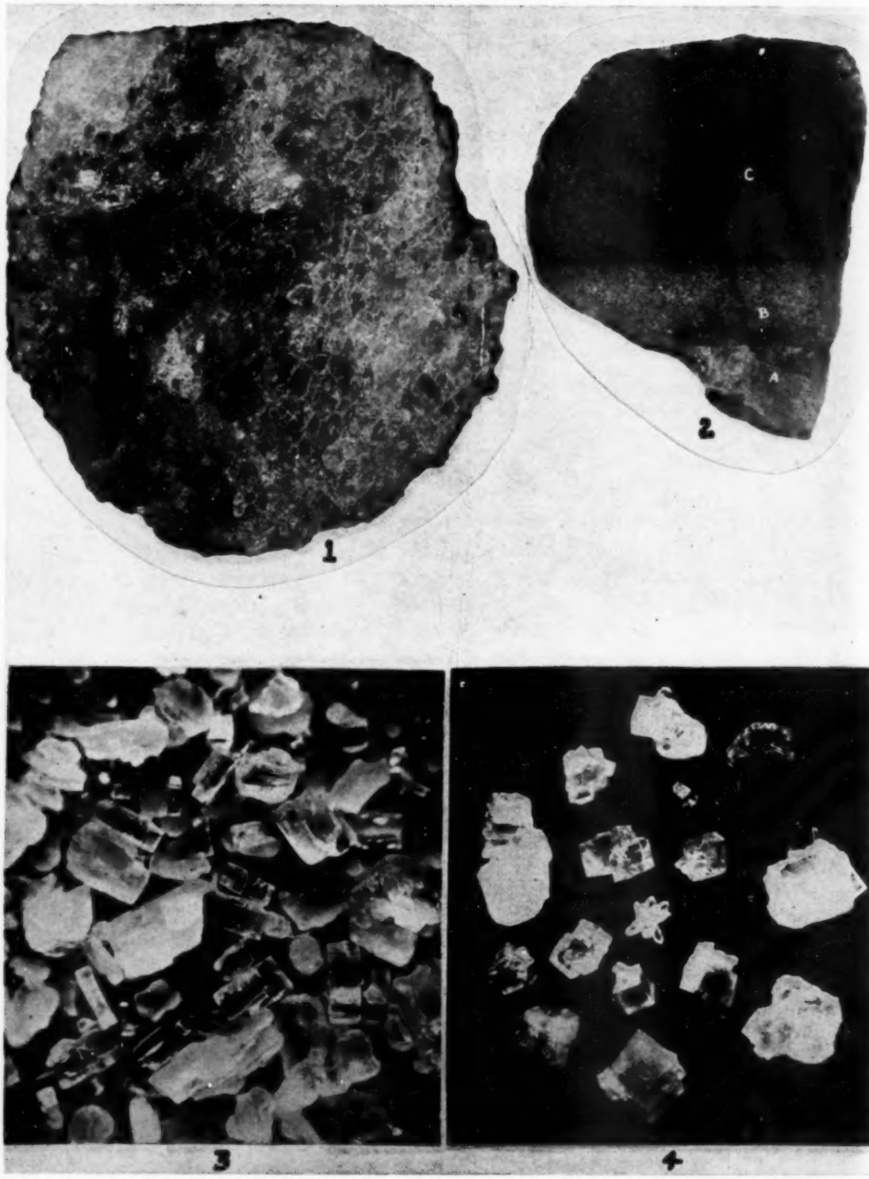
| *Mineral Name* | *Composition* | *Remarks* |
|---|---|---|
| Anhydrite | $CaSO_4$ | |
| Gypsum | $CaSO_4 + 2H_2O$ | Variety, rock gypsum |
| Gypsum | $CaSO_4 + 2H_2O$ | Variety, selenite |
| Gypsum | $CaSO_4 + 2H_2O$ | Variety, satin spar |
| Gypsum | $CaSO_4 + 2H_2O$ | Variety, alabaster |
| Barite | $BaSO_4$ | Variety, massive |
| Barite | $BaSO_4$ | Variety, oölitic |
| Celestite | $SrSO_4$ | |
| Calcite | $CaCO_3$ | |
| Aragonite | $CaCO_3$ | |
| Strontianite | $SrCO_3$ | |
| Smithsonite | $ZnCO_3$ | |
| Dolomite | $CaCO_3 \cdot MgCO_3$ | |
| Pyrite | $FeS_2$ | |
| Marcasite | $FeS_2$ | |
| Galena | $PbS$ | |
| Sphalerite | $ZnS$ | |
| Hauerite | $MnS_2$ | |
| Alabandite | $MnS$ | |
| Realgar | $As_2S_2$ | |
| Chalcopyrite | $CuFeS_2$ | |
| Chalcocite | $Cu_2S$ | |
| Enargite | $Cu_3AsS_4$ | |
| Halite | $NaCl$ | |
| Quartz | $SiO_2$ | |
| Hematite | $Fe_2O_3$ | |
| Sulphur | — | |
| Arsenic | — | |

Table I lists the minerals known to the writers to have been found to date.

In addition to these, an unidentified, green copper mineral, probably a chloride, and a pseudomorph of calcium carbonate and sulphate after hauerite have been found. A small quantity of potassium salts was found in the salt of one dome. Arsenic and antimony minerals are minute in quantity and to date have been recognized in the cap rock of only one dome.

## DISTRIBUTION OF MINERALS

The three chief minerals of cap rocks, as already mentioned, are anhydrite, gypsum, and calcite. In general, without discussing individual domes in detail, or exceptional cases, anhydrite forms the major part of all caps and lies directly on the massive salt plugs. Above the anhydrite zone is the gypsum-anhydrite zone. If calcite rock is present, it is on top. Then the gypsum-anhydrite zone contains considerable calcite and forms a transition zone between the calcite and anhydrite. Over what is called the "true cap" of many domes, the gumbos and sands normally present have been more or less calcified, and this partly calcified material is called "false cap."




## PLATE 1

FIG. 1.—Massive rock salt. Depth, 700 feet. Morton Salt Company mine, Grand Saline dome, Van Zandt County, Texas. In darker areas concentration of disseminated anhydrite is greater. ×0.325.

FIG. 2.—Main salt-anhydrite contact. Houston Salt Company shaft, Hockley dome, Harris County, Texas. *A*—massive salt; *B*—transition zone in which disseminated anhydrite crystals are still in salt matrix; *C*—massive anhydrite consisting of compacted crystals similar to those in zones *A* and *B*. Banding is due chiefly to iron sulphide. ×0.733.

FIG. 3.—Anhydrite crystals from typical salt-anhydrite residue after leaching massive salt with water. 300 feet below main salt-anhydrite contact (Fig. 1). ×16.0.

FIG. 4.—Calcite and quartz crystals picked from residue shown in Figure 3. Such crystals together with sulphur are rare in most salt residues. ×16.0.

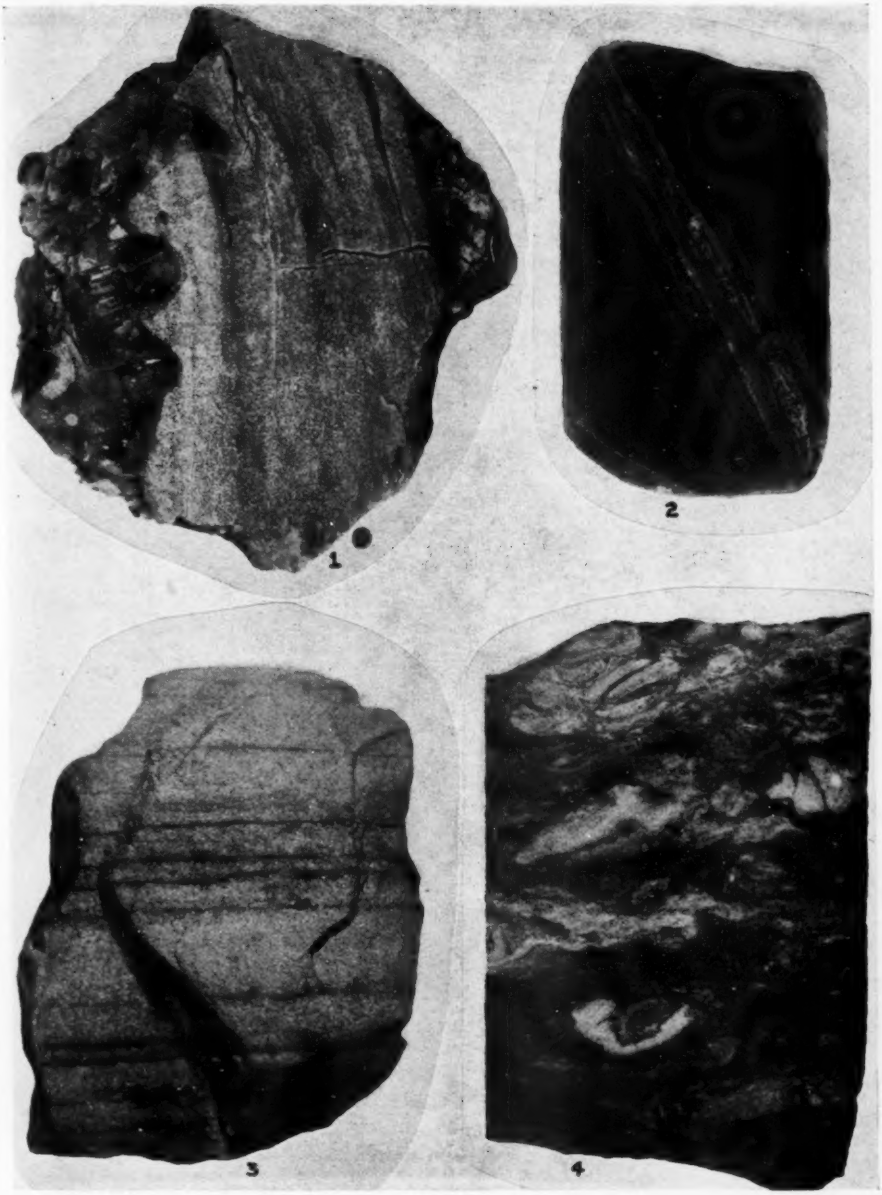


PLATE 2

FIG. 1.—Gypsum (dark), anhydrite (light) from dump made when sinking shaft of Morton Salt Company, Grand Saline dome. ×0.306.

FIG. 2.—Core of schistose anhydrite from Gulf dome, Matagorda County, Texas. Small gouge zone passes through center of core. ×0.43.

FIG. 3.—Banded anhydrite from lower part of anhydrite section in Houston Salt Company shaft, Hockley dome. ×0.57.

FIG. 4.—Polished anhydrite core from Gulf dome, Matagorda County. ×0.59.


PLATE 3

FIG. 1.—*A*—satin spar gypsum; *B*—sulphur from Newgulf dome, Wharton County, Texas. ×1.35.

FIG. 2.—Banded limestone cap rock from Thibodeaux dome, La Fourche Parish, Louisiana. ×0.84.

FIG. 3.—Banded limestone cap rock from Pine Prairie dome, Evangeline Parish, Louisiana. ×0.61.

FIG. 4.—Banded limestone cap rock from Winnfield dome, Winn Parish, Louisiana. ×0.61.

FIG. 5.—Anhydrite and quartz sand from lower part of anhydrite section in shaft of Houston Salt Company, Hockley dome, Harris County, Texas. ×0.72.


PLATE 4

FIG. 1.—*A*—drusy calcite which is secondary over *B*—sulphur, from Newgulf dome, Wharton County, Texas. ×0.66.

FIG. 2.—Sulphur and limestone cap rock. Note *A*—fibrous sulphur crossing cavities. ×0.96.

FIG. 3.—Sulphur crystals in cavernous limestone cap rock from Gulf dome, Matagorda County, Texas.

FIG. 4.—*A*—selenite gypsum; *B*—sulphur from Newgulf dome, Wharton County, Texas. ×0.9.

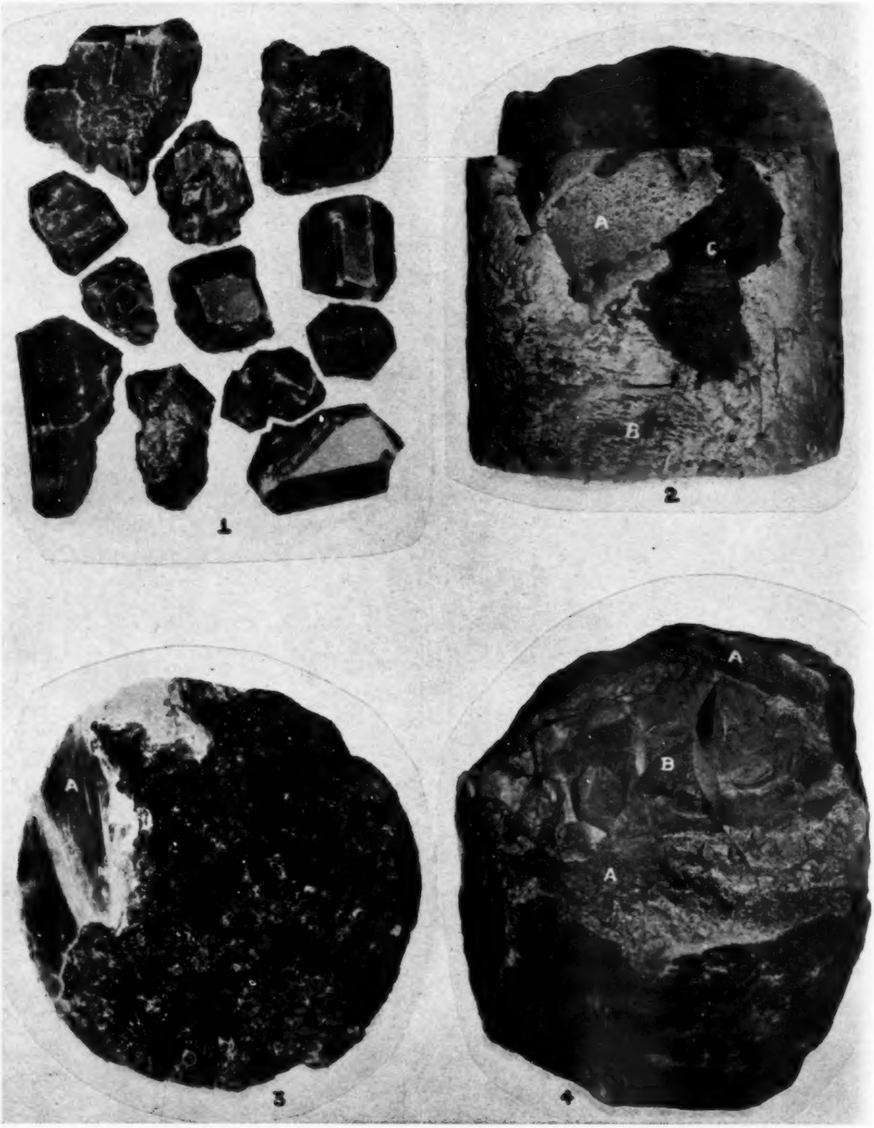



PLATE 5

FIG. 1.—Sulphur crystals. ×0.5.
FIG. 2.—*A*—anhydrite; *B*—alabaster; *C*—sulphur from Newgulf dome, Wharton County, Texas. ×0.73.
FIG. 3.—*A*—selenite, cavernous limestone cap rock, and sulphur from Newgulf dome. ×0.68.
FIG. 4.—*A*—anhydrite; *B*—amorphous sulphur. ×0.83.

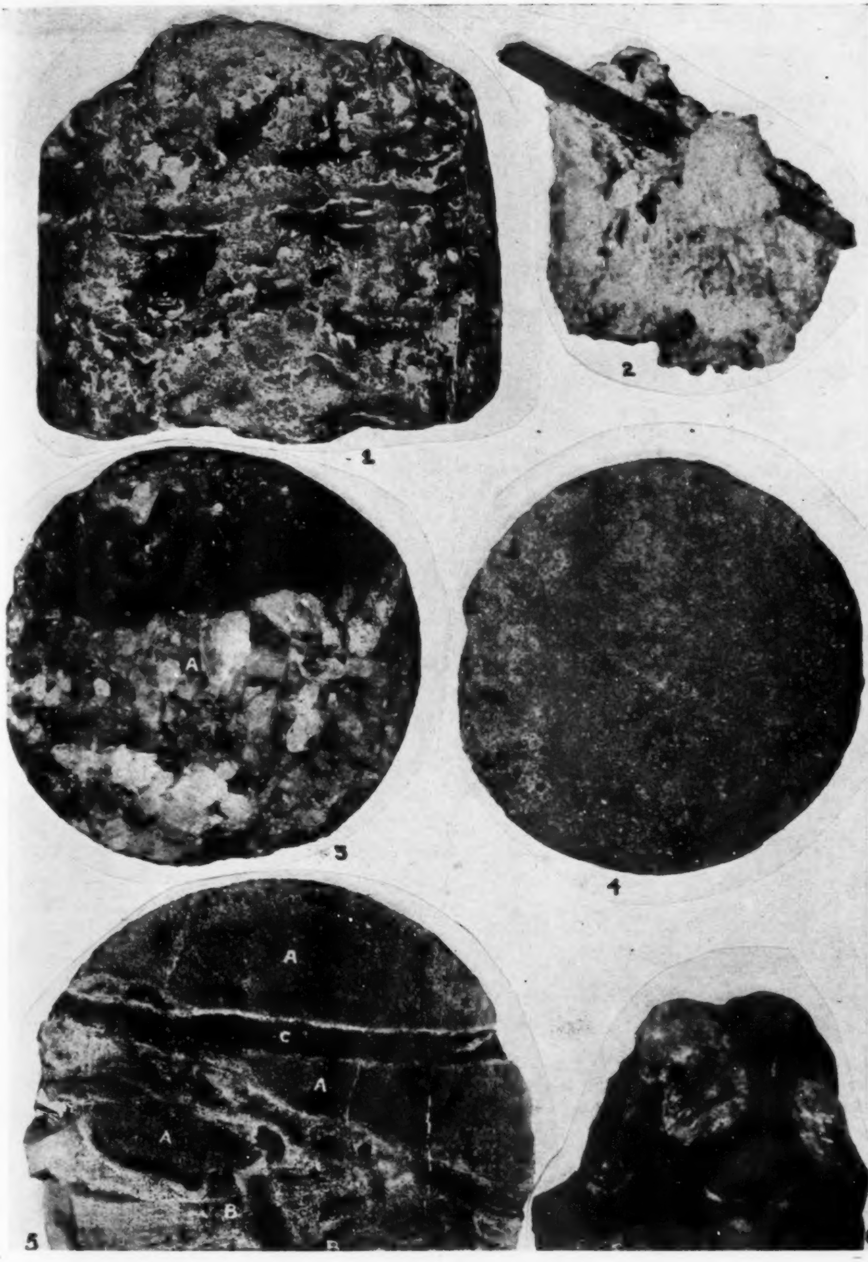



PLATE 6

FIG. 1.—Cavernous limestone cap rock and sulphur from Newgulf dome, Wharton County, Texas. ×0.71.

FIG. 2.—Quartz crystal from Palangana dome, Duval County, Texas. ×1.56.

FIG. 3.—*A*—celestite on limestone cap rock from Newgulf dome. ×0.9.

FIG. 4.—Galena from Gulf dome, Matagorda County, Texas. ×0.68.

FIG. 5.—*A*—anhydrite; *B*—vein selenite; *C*—vein of sulphur edged with calcite from Newgulf dome. ×0.71.

FIG. 6.—Marcasite from Gulf dome. ×0.94.

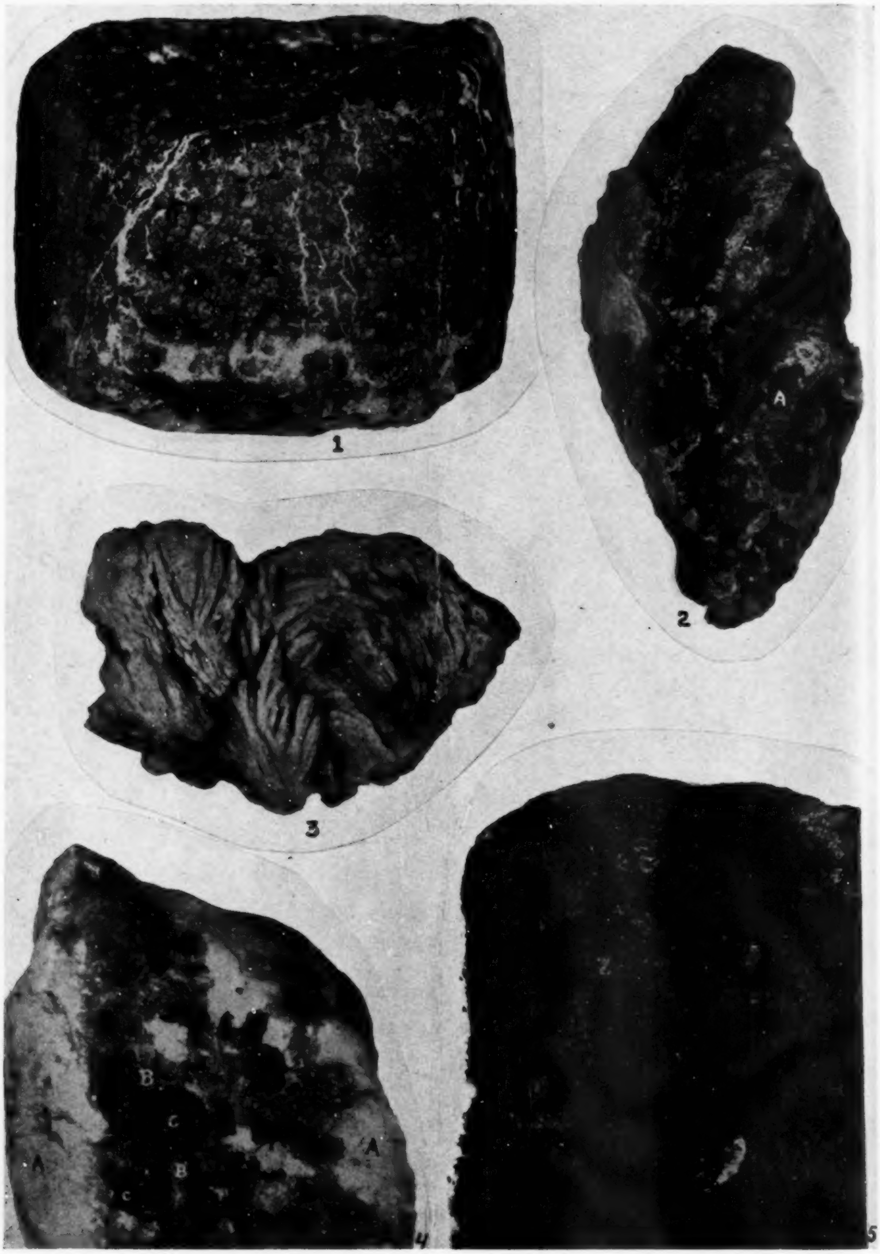


PLATE 7

FIG. 1.—Amorphous sulphur in vesicular limestone cap rock. ×0.83.
FIG. 2.—*A*—alabandite from Gulf dome, Matagorda County, Texas. ×1.16.
FIG. 3.—Barite from Newgulf dome, Wharton County, Texas. ×1.65.
FIG. 4.—*A*—calcite; *B*—sulphur; *C*—sphalerite from Hoskins Mound, Brazoria County, Texas. ×1.15.
FIG. 5.—Smithsonite from Palangana dome, Duval County, Texas. ×1.6.

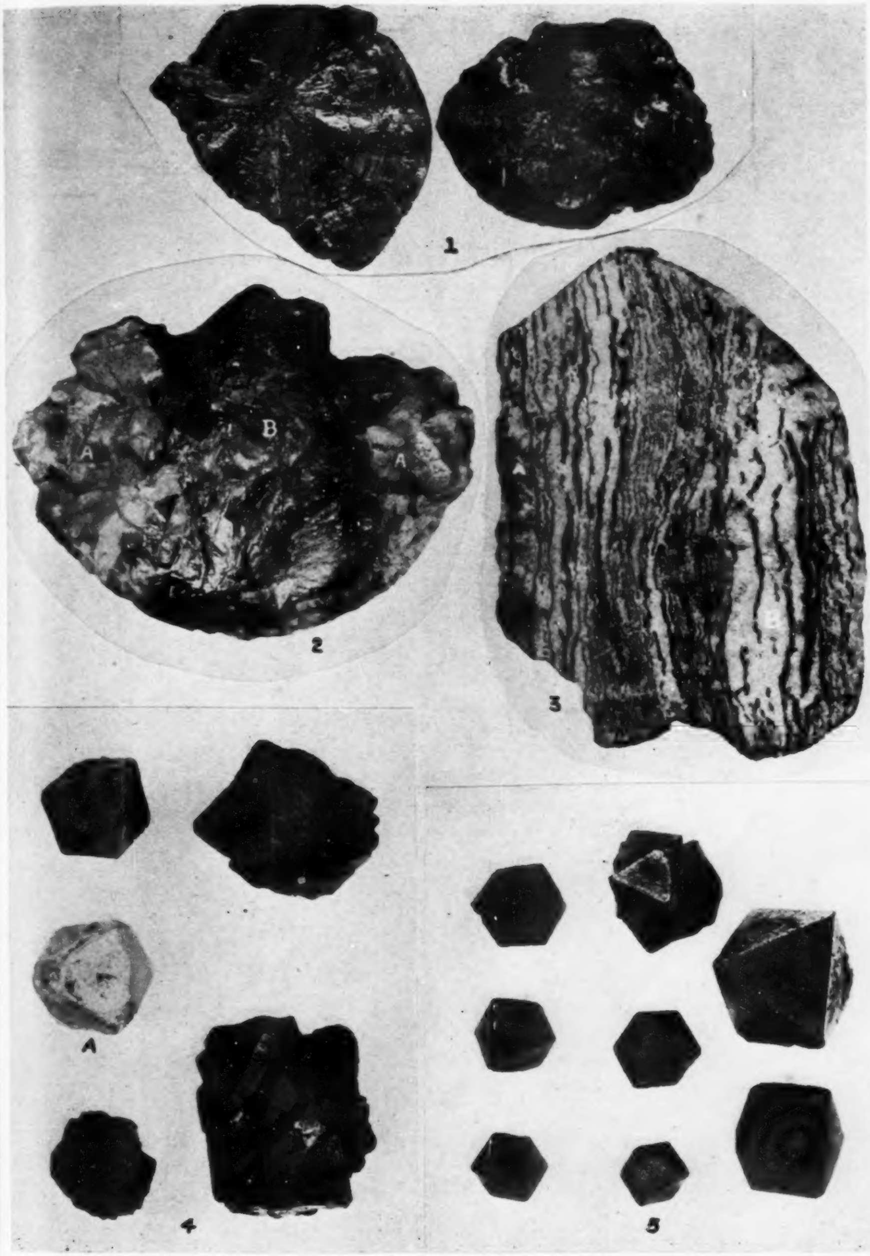



PLATE 8

FIG. 1.—Two views of hauerite nodule from Gulf dome, Matagorda County, Texas. ×0.66.
FIG. 2.—*A*—celestite; *B*—sulphur from Newgulf dome, Wharton County, Texas. ×0.83.
FIG. 3.—*A*—sulphur; *B*—barite from Gulf dome. ×0.83.
FIG. 4.—Four hauerite crystals; *A*—pseudomorph after hauerite from Gulf dome. ×1.0.
FIG. 5.—Eight hauerite crystals from Gulf dome. ×1.31.

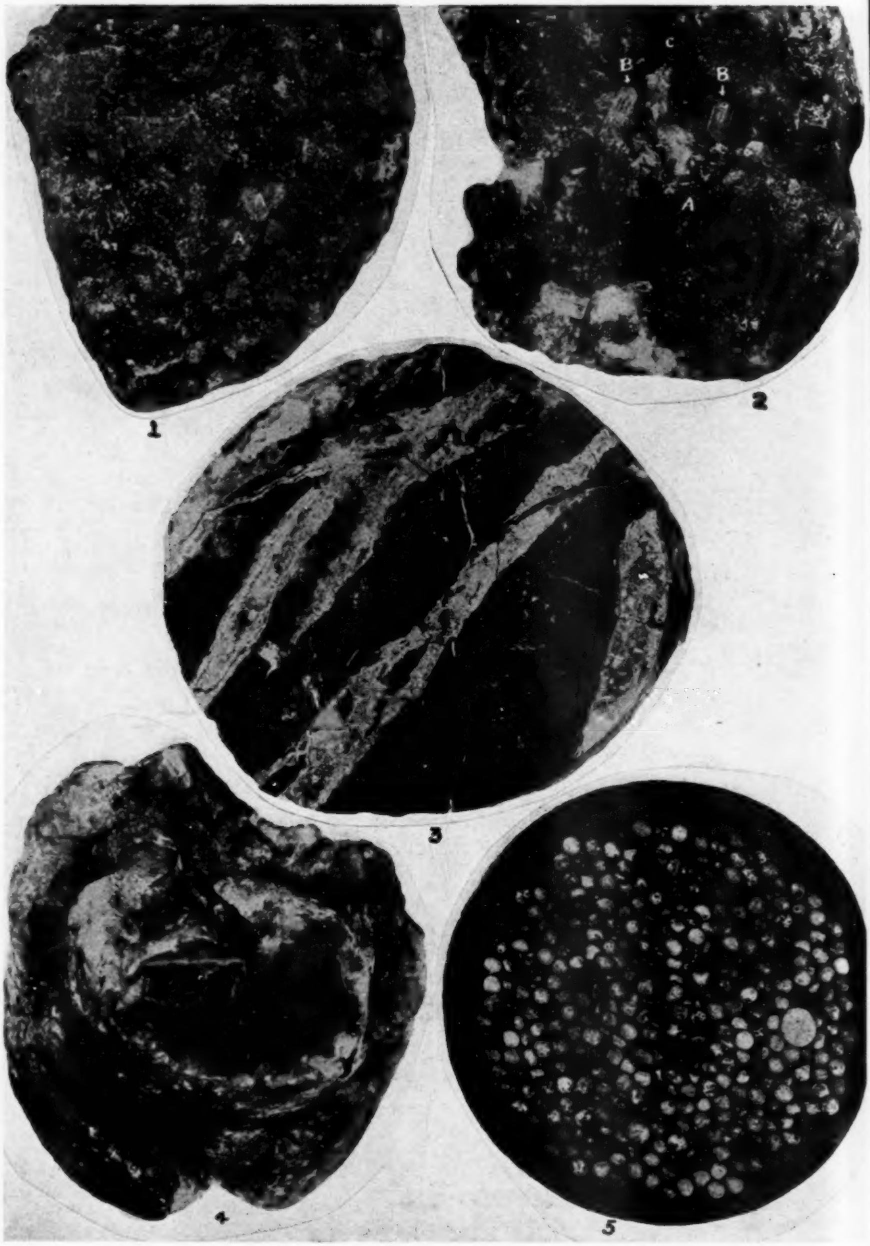



PLATE 9

FIG. 1.—*A*—sphalerite and other sulphides from Gulf dome, Matagorda County, Texas. ×1.25.

FIG. 2.—*A*—limestone cap rock; *B*—aragonite; *C*—sulphur from Palangana dome, Duval County, Texas. ×0.8.

FIG. 3.—Sulphide mud with abundant galena crystals from Gulf dome. ×0.83.

FIG. 4.—Aragonite from Starks dome, Calcasieu Parish, Louisiana. ×0.70.

FIG. 5.—Barite oölites from Batson dome, Hardin County, Texas. ×0.91.

PLATE 10

FIG. 1.—*A*—hauerite crystal in limestone cap rock from Gulf dome, Matagorda County, Texas. ×1.08.
FIG. 2.—*A*—barite; *B*—sulphur from Gulf dome. ×0.69.
FIG. 3.—Pyrite and calcite from Gulf dome. ×0.72.
FIG. 4.—*A*—barite; *B*—sulphur; *C*—calcite from Newgulf dome, Wharton County, Texas. ×0.5.

Free sulphur is present in practically every dome cap, but in commercial quantity in only some of the domes having a thick calcite zone. Considerable sulphur extends into the gypsum transition zone (Pl. 5, Fig. 2, and Pl. 6, Fig. 5), and occurs only in minute quantity in the anhydrite below. Microscopically, it may be found anywhere in the anhydrite and rarely even in the salt stock.

As would be supposed, the carbonate minerals, strontianite and aragonite, occur chiefly in the calcite zone, although dolomite is found chiefly in the anhydrite as microscopic crystals. Barite and celestite also occur mainly in the calcite zone, but both are found microscopically in the anhydrite.

Of the sulphide minerals, pyrite is the most common and has been found in all zones of the cap rock. Galena and sphalerite are found, for the most part, in the calcite rock, although some patches of "earthy" sphalerite have been found cementing grains of anhydrite. In two cases galena, and in one sphalerite, have been recognized in offside sediments at depths ranging from 4,000 to 4,500 feet. The rare manganese sulphide hauerite occurs, in the macroscopic crystalline form, chiefly in the false cap and the calcite cap. Some crystals are found in anhydrite, where, like sphalerite, it is also found as a cementing material between crystals of anhydrite. The only alabandite specimen found to date came from the false cap or very top of the calcite cap.

Arsenic, arsenic sulphides, copper sulphides, and copper arsenosulphides are reported from only one dome, Winnfield, Louisiana (14).[4] These minerals were found at a place on the mine dump, indicating that they occurred in the basal portion of the anhydrite. An unidentified green copper mineral was found deep in the anhydrite at Hockley (11) and at Winnfield by the writers.

Quartz, in microscopic crystals, is common in the anhydrite portion of the caps. Only one macroscopic crystal has been found by, or called to the attention of, the writers (Pl. 6, Fig. 2). This was washed up from the very bottom of the anhydrite or the top of the salt stock, and has some anhydrite adhering to it.

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[4] Numbers in parenthesis refer to Bibliography at end of paper.

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VOL. 18, NO. 2 (FEBRUARY, 1934), PP 226-242, 2 FIGS.

# NATURAL GAS IN AUSTRALIA AND NEW GUINEA[1]

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## ABSTRACT

Inflammable natural gas, in amounts exceeding several million cubic feet, has been found in wells drilled at Roma in Queensland. Small amounts of natural gas, accompanying artesian water, are commonly encountered in wells drilled in parts of the Great Artesian basin. According to location two types of gas are encountered in the Great Artesian basin region: (1) an inflammable hydrocarbon gas; and (2) a non-inflammable nitrogen gas, containing no hydrocarbons. The carbon dioxide type of gas is found in parts of New South Wales and Victoria.

## INTRODUCTION

Though oil and natural gas have not been discovered in large amounts in Australia and in those parts of New Guinea which are under Australian control, sufficient has been found to indicate that the search for both oil and gas is justifiable.

According to the indications, natural gas in these regions may be classified as: (1) derived from recent and sub-recent sediments, (2) derived from carbonaceous strata, (3) associated with artesian water, (4) derived from metamorphic rocks, and (5) presumably associated with petroleum.

## NATURAL GAS DERIVED FROM RECENT AND SUB-RECENT SEDIMENTS

Much of the coast line of Australia shows evidence of having been produced by the drowning, in sub-recent time, of a land surface of immature or early mature character. Some of the juvenile or adolescent river valleys still remain as magnificent harbors. Where, however, the process of drowning left the remnants of the streams in an active condition, the submerged valleys have been filled completely with sediment. The large amount of vegetable matter in these sediments causes considerable evolution of marsh gas. In some places, this is so prolific as to suggest to the layman the possibility of commercial supplies. Considerable amounts of money have been wasted in searching for oil and gas in these drowned river valleys, which is the sole reason for including mention of them in this sketch. Many of the so-

[1] Manuscript received, September 14, 1932. Published by permission of the Honourable the Minister for the Interior, Archdale Parkhill.

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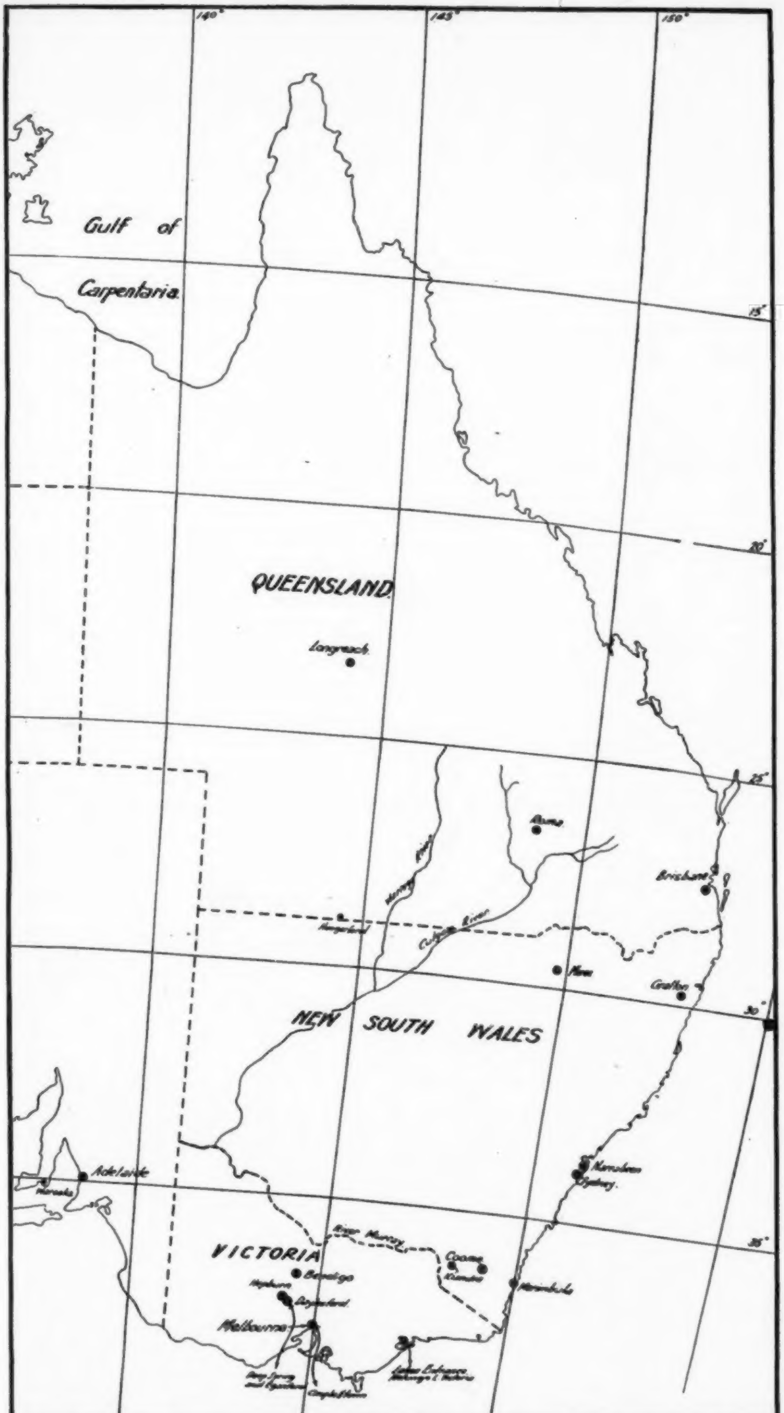


FIG. 1.—Sketch map of Queensland, New South Wales, and Victoria, showing locations mentioned.

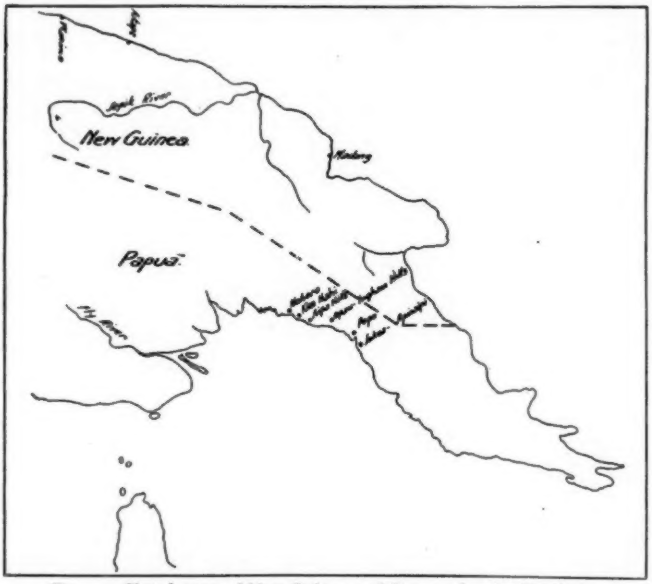


FIG. 2.—Sketch map of New Guinea and Papua, showing locations mentioned. East-west distance, approximately 650 miles.

called prospects must be included here—for example, that at Merimbula, on the south coast of New South Wales.

TABLE I

GEOLOGICAL FORMATIONS OF COMMONWEALTH OF AUSTRALIA

(Abridged and somewhat generalized from T. W. E. David, *Explanatory Notes to Accompany a New Geological Map of the Commonwealth of Australia*, The Commonwealth Council for Scientific and Industrial Research, Sydney, 1932.)

| | |
|---|---|
| | CENOZOIC |
| POST-TERTIARY | |
| | Coral reefs, raised reefs, dunes, alluvial deposits and some volcanic rocks |
| TERTIARY | |
| Pliocene to Pleistocene | Werrikooian series (Victoria), Upper Wanimo series (New Guinea) |
| Pliocene | Kalimnan series (Victoria), Finsch Coast series and Lower Wanimo series (New Guinea), Upper Purari series (Papua) |
| Miocene | Janjukian series (Victoria), Aldingan series (South Australia), Plantagenet beds (West Australia), Upper Aitape series (New Guinea), Lower Purari series (Papua) |
| Oligocene | Balcombian series (Victoria), Exmouth Gulf beds (West Australia), Lower Aitape series (New Guinea) |
| Eocene | Eyrian series (South Australia), Mebu series (New Guinea), Upper Port Moresby beds (Papua) |
| | MESOZOIC |
| CRETACEOUS | |
| Upper | Gin Gin beds (West Australia), Winton (lacustrine) and Tambo (marine) series of Queensland, New South Wales, and South Australia |

TABLE I (*Continued*)

| | |
|---|---|
| Lower | Burrum Coal measures (Queensland), Roma and Maryborough series (marine, Queensland). Equivalents in other states |
| JURASSIC | |
| | Walloon series (continental), (Queensland), Clarence series (in part, New South Wales), Wonthaggi Coal measures (Victoria), Bundanba series (Queensland). Minor developments in other states |
| TRIASSIC | |
| | Upper Hawkesbury series (fresh water, New South Wales). Equivalents in other states |
| | PALEOZOIC |
| PERMO-CARBONIFEROUS | |
| | Kamilaroi series. Marine beds, Coal measures, glacials, and volcanic rocks of all states. A definite geological unit the lower part of which is Carboniferous, the upper part Permian |
| CARBONIFEROUS | |
| | Lower part of Kamilaroi series including Gympie series of Queensland |
| Lower to Upper | Kuttung series (New South Wales), glacial and volcanic largely |
| Lower | Neerkol and Rockhampton series (Queensland), Burindi series (New South Wales), and extensive developments in Kimberley Division of West Australia |
| CARBO-DEVONIAN | |
| | Grampian and Mansfield series (Victoria), Drummond and Upper Star series (Queensland) |
| DEVONIAN | |
| Upper | Avon River and Iguana Creek beds (Victoria), Lambian and Barraba series (New South Wales), Berserker and Mt. Wyatt (?) series, Queensland) |
| Middle | Tamworth and Murrumbidgee series (New South Wales), Burdekin, Silverwood, and Lower Star series (Queensland), Buchan and Bindi series (Victoria) |
| Lower | Snowy River series (Victoria). Equivalents in other states |
| SILURIAN | |
| Upper | Walhalla and Yeringian series (Victoria), Yass, Bowning, Orange, and Wellington series (New South Wales), Chillagoe series (Queensland) |
| Lower | Zeehan and West Coast series (Tasmania), Melbournian (Victoria) |
| SILURO-ORDOVICIAN | |
| | Crystalline schist series (Victoria) |
| ORDOVICIAN | |
| Upper | Larapintine (Northern Territory), Glenormiston beds (in part, Queensland), Upper Graptolite beds of Victoria and extensions into New South Wales |
| Lower | Darriwillian, Castlemainian, Bendigonian, and Lancefieldian series (Victoria), Glenormiston beds (in part, Queensland) |
| CAMBRO-ORDOVICIAN | |
| | Dundas slates and Porphyroid series and Cambro-Ordovician limestones (Tasmania) |
| CAMBRIAN | |
| Upper | Dolodrook series (Victoria), Caroline Creek and Frenchman's Cap series (Tasmania) |
| Middle | Heathcotian series (Victoria), Templeton River and Yelvertoft beds (Queensland), Alroy Downs beds (Northern Territory), *Girvanella* and *Obolella* beds (South Australia) |
| Lower | *Girvanella* beds (Northern Territory), *Redlichia* zones (West Australia and South Australia), *Archaeocyathinae* limestones (South Australia) |
| PRE-CAMBRIAN (?) | |
| | Purple Slate series (South Australia and Northern Territory) |
| PRE-CAMBRIAN | |
| | Archeozoic and Proterozoic series in great variety extensively developed chiefly in western half of continent |

Evolution of gas in large amounts has been associated with the appearance and periodic re-appearance of a transient mud island in Lake Victoria, Gippsland, in the state of Victoria. Though these phenomena have been held by some to be connected with deep-seated oil fields, the personal opinion of the writer is that the gas originates from recent lacustrine deposits.[3]

The composition of the gas does not suggest connection with petroleum, as the analysis of Table II shows. Owing to the tropical climate and vegetation, evolution of marsh gas from recent detritus is widespread and plentiful both in Papua and New Guinea.

TABLE II

| *Constituents* | *Percentage* |
|---|---|
| Carbon dioxide | 24.4 |
| Oxygen | 0.8 |
| Methane | 62.5 |
| Nitrogen | 12.3 |
| | 100.0 |

### NATURAL GAS DERIVED FROM CARBONACEOUS STRATA

Australia possesses extensive reserves of bituminous, semi-bituminous, and brown coal. These range in age from Permian to Tertiary, the principal black coals being of Permian, Triassic, and Jurassic age. As is to be expected, the normal gases associated with coal measures are encountered wherever these coals are sufficiently deeply buried, or where the measures have been intruded by igneous rocks. Gases in the former category do not merit special mention, although they have been the cause of more than one fruitless attempt to search for oil.

It is in those instances where the genetic association of gas with coal is less obvious that greater interest is aroused.

At Narrabeen, near Sydney, the capital of New South Wales, somewhat extensive prospecting operations in search of oil have been carried out on the strength of the discovery of considerable amounts of natural gas during drilling operations. The association of this gas with the Permian coal measures is so obvious as to call for no further comment.

Of more interest, and of more debatable character, are those gas occurrences in the Mesozoic rocks of the Clarence River Basin in northeasten New South Wales, and of the Ipswich Basin (in a broad sense) in the adjacent part of Queensland.

The Ipswich Coal measures of Queensland, producing most of the coal there, are of Triassic age. Very recently, drilling for oil has been

[3] W. G. Woolnough, "Origin of Mud Island near Paynesville, Victoria," *Proc. Roy. Soc. Victoria*, Vol. 13, Pt. 2, New Ser. (1930).

undertaken in the vicinity of Brisbane, the capital, and it has been claimed that good indications of oil and gas have been encountered. As operations are still in progress at the time of writing, it is too early to state to what extent the prevailing optimism is justified, and whether or not the "indications" have been derived from indigenous oil, or from the distillation of coal by volcanic heat. Certain it is that the Mesozoic rocks in this part of Queensland are seamed with basaltic dikes, so that all the conditions for extensive destructive distillation of the contained plant materials are present.

Several occurrences of "natural gas" in the Brisbane basin have been officially investigated. Though the evidence is by no means conclusive, the balance of probability favors the view that the gases in question may have been derived from coal.

Typical analyses are shown in Table III.

TABLE III

CONSTITUENTS IN PERCENTAGE

| *Sample Number* | $CO_2$ | *Air* | $CH_4$ | *Inert* |
|---|---|---|---|---|
| 1 | 0.5 | 2.5 | 57.0 | 40.0 |
| 2 | 0.5 | 9.5 | 55.0 | 35.0 |
| 3 | 1.0 | 12.0 | 69.3 | 17.7 |
| 4 | 0.5 | 10.0 | 67.5 | 22.0 |

Overlying the Ipswich Coal measures are Jurassic continental beds, known as the Walloon measures. These also are coal-bearing; the coals are softer than those of the Ipswich measures. These Walloon beds extend southward into New South Wales, where they occupy an extensive geosyncline referred to as the Clarence River Coal basin.

It is incorrect to class this system as a purely "fresh-water system," as there are intercalations of saliferous beds in the series. It is more strictly correct to refer to the formation as "non-marine," as the saliferous horizons give evidence of having been formed under continental conditions.

It seems doubtful that purely continental formations can be considered favorable for the development of indigenous petroleum. The great hopes which are entertained of developing payable oil fields in these formations are most probably exaggerated.

Many reports of the discovery of natural gas have been made about the Walloon and Clarence series. The most noteworthy example is that supplied by the Grafton well. Grafton is the most important town on Clarence River in New South Wales. A well was drilled here in 1901, primarily in search of artesian water. Potable water was en-

countered at 1,070 feet. At first this flowed freely at the surface, but subsequently receded, though it continued to rise nearly to the surface. From 1,070 feet to the bottom of the well at 3,700 feet, no further water was found. Coaly streaks were intersected at 2,205, 2,288, and 3,366 feet, and a 7-foot seam of coal at 3,419 feet.

Gas was found at approximately 3,100 feet, but there is no official record of the exact depth. At times the pressure of the gas was sufficient to throw the water halfway up the derrick. In May, 1901, the gas was ignited from a forge 14 feet away, and burned with a flame 4 feet high, which it was difficult to extinguish. In 1911 it gave a feeble flame 1.5 inches high, which could be blown out with a breath. When examined by the writer in 1927 the gas could be made to burn only intermittently, as the flame each time ran along the casing and extinguished itself.[4]

The gas was analyzed in 1916. Two samples taken within 45 minutes of one another, and with due precautions to avoid contamination with air, gave markedly different results. Ethane, ethylene, hydrogen,

TABLE IV

| *Constituents* | *Percentage* | |
|---|---|---|
| Methane | 62.50 | 86.95 |
| Oxygen | 10.66 | 5.53 |
| Nitrogen | 26.84 | 7.52 |
| | 100.00 | 100.00 |

and oxides of carbon were absent, and the gas, tested at the well, gave no reaction for sulphuretted hydrogen. The flow of gas was very spasmodic.[5]

Very recently extremely small amounts of gas were encountered in a well near Grafton, which has been sunk in search of oil on the strength of "divining." Though insignificant in amount, this gas is interesting in composition (Table V).

TABLE V

| *Constituents* | *Percentage* |
|---|---|
| Carbon dioxide | 0.2 |
| Oxygen | Trace |
| Carbon monoxide | Nil |
| Hydrogen | Nil |
| Sulphuretted hydrogen | Nil |
| Methane | 83.8 |
| Ethane | 5.5 |
| Nitrogen | 10.5 |
| | 100.0 |

[4] J. E. Carne, "Notes on the Occurrence of Coal, Petroleum and Copper in Papua," *Territory of Papua Bull. 1* (1913), p. 77.

[5] L. J. Jones, "Notes on Petroleum and Natural Gas, and the Possibilities of Their Occurrence in New South Wales," *Geol. Survey New South Wales Min. Resources 31* (Sydney, 1921), p. 34.

Naturally those interested in the search for oil in the district interpret the analysis as indicative of the derivation of the gas from petroleum. Though such an origin is possible, it seems advisable to exercise caution. In view of the known existence of abundant coaly material in the formation, and of much volcanic activity during Tertiary time, it seems not improbable that the gas, with or without small amounts of oil, may have been produced from the coal by destructive distillation.

Contradictory opinions have been expressed about gas encountered in the Robe well in southeastern South Australia. The official report by the Government geologist of South Australia[6] strongly suggests that the gas (Table VI), found at 3,010 feet, is derived from fresh-water beds of Jurassic age.

TABLE VI

| *Constituents* | *Percentage* |
|---|---|
| Carbon dioxide | 1.3 |
| Oxygen | 3.0 |
| Methane | 39.6 |
| Hydrogen | 25.4 |
| Nitrogen (difference) | 30.7 |
| | 100.0 |

In Papua and New Guinea, natural gas, believed to originate from carbonaceous rocks of Tertiary age, has been recorded in several places, chiefly in the Mandated Territory of New Guinea in the hinterland of Madang, in Duene River, and at Keku, Ousup, and Ouso.[7]

In Duene River, the gas (Table VII) rises briskly through three vents from steeply dipping beds of Miocene age, in the vicinity of an extensive fault.

TABLE VII

| | | |
|---|---|---|
| | $CO_2$ | 1.9 |
| Air | $O_2$ | 0.9 |
| | $N_2$ | 3.6 |
| Condensable hydrocarbons | | 6.2 |
| Uncondensable hydrocarbons (ethane and methane) | | 87.4 |

At Keku, brine accompanied by gas issues from several small vents. The spring is situated near a fault marking the junction between two series of rocks, one highly metamorphosed and indurated, the other carbonaceous in character and much less altered. The gas

[6] L. K. Ward, *South Australia Review of Mining Operations 25* (1916), pp. 47 and 48.

[7] *The Oil Exploration Work in Papua and New Guinea Conducted by the Anglo-Persian Oil Company on Behalf of the Government of the Commonwealth of Australia, 1920–1929* (London, 1931). 4 Vols. See Vol. 2.

escaping from some vents is highly inflammable; from others it seems to be largely carbon dioxide or nitrogen, as it extinguishes a flame held near it.

At Ousup and Ouso inflammable gas is given off by brine springs.

None of the gas emanations possesses an odor and none is associated with an oil film.

### NATURAL GAS ASSOCIATED WITH ARTESIAN WATER

Australia is somewhat remarkable for the number and extent of its artesian basins, in every state on the mainland. One of these, referred to as the Great Artesian basin, is the largest known structural feature of its kind. Occupying about one-third of the area of Queensland, and with considerable extensions into New South Wales, South Australia, and the Northern Territory, it includes an area of 600,000 square miles.

Structurally it is a geosyncline, bounded on the east and west by older formations. On the south the older rocks which form the margin of the basin in that direction are hidden under younger formations. Toward the north the basin opens into the Gulf of Carpentaria. The principal aquifers are porous beds of the Jurassic Walloon series. As already mentioned, these rocks are continental deposits, and, though they contain saliferous phases, do not present any evidence of marine conditions. Their relationship to the indications of petroleum in Queensland is considered in the classification of natural gas, presumably associated with petroleum.

Gases other than those more or less directly associated with oil indications are plentiful in parts of the basin, and exhibit interesting features. The gases are associated with the individual aquifers, the number of which varies in different parts of the basin.

Two essentially different types of gas are encountered, namely, inflammable gases composed essentially of methane, and gases almost completely nitrogenous. Table VIII gives analyses selected as being typical of the different modifications of composition.

The inert gases of the typical Warrego wells are ordinarily in such small quantities as to be unnoticeable.

West of the Eulo-Hungerford submerged ridge, and east of Bundaleer ridge (midway between the Warrego and Culgea at the border fence), the gases carry methane, whereas between those ridges, the typical Warrego gases are ordinarily more than 99 per cent inert.

Most of the central and northern gases are inflammable.

An interesting experiment was carried out by the State drilling department in New South Wales, in isolating the different flows from

TABLE VIII

| Well | Water Zone | Year Sampled | Water Temp. Deg. F. | Cu. Ft. Gas per 1,000 Gal. | Per-cent by Vol. | Constituents (Per Cent) | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | $CO_2$ | $O_2$ | $H_2$ | $N_2$ | $CH_4$ |
| Florida | Main | 1924 | 117 | 0.97 | 0.60 | 0.60 | 1.0 | 0.0 | 98.4 | 0.0 |
| Florida | Main | 1928 | | 0.83 | 0.52 | 0.00 | 0.0 | 0.0 | 100.0 | 0.0 |
| Florida | Upper | 1928 | | | | 0.60 | 0.0 | 9.5 | 58.1 | 31.8* |
| Moomin | Main | 1924 | 107 | 0.65 | 0.404 | 0.00 | 0.0 | 0.0 | 100.0 | 0.0 |
| Krui | Main | 1924 | 107 | 0.48 | 0.30 | 0.00 | 3.0 | 0.0 | 97.0 | 0.0 |
| Mungyer | Main | 1928 | | 0.69 | 0.431 | 0.60 | 0.8 | 0.0 | 98.6 | 0.0 |
| Mungyer | Upper | 1928 | | | | 0.40 | 1.4 | 17.4 | 38.0 | 42.8* |
| Quilbone 1 | First | 1924 | 92 | 0.031 | 0.019 | 0.60 | 0.8 | 0.0 | 98.6 | 0.0 |
| Coonamble 1 | | | 96 | | | 2.40 | 4.0 | 0.0 | 93.6 | 0.0† |
| Coonamble 2 | | | 102 | | | 4.16 | 7.5 | 0.0 | 86.6 | 0.0†·‡ |
| Urawilkie 1 | | | 87 | | | 10.50 | 0.0 | 0.0 | 89.5 | 0.0† |
| Currumbah | | | 101 | | | 4.16 | 0.0 | 0.0 | 56.1 | 39.7§ |
| Keelendi | | | 113 | | | 0.00 | 12.5 | 0.0 | 87.5 | 0.0§ |
| Iffley 1 | | | | | | 8.90 | | | | 57.1‖ |
| Mt. Howitt | | | | | | 0.00 | | | | 69.7¶ |

* Gas burns quietly when ignited.
† Pipe corrosion.
‡ CO, 1.7.
§ No pipe corrosion.
‖ Inert, 34.0.
¶ Inert, 30.3.

a typical well, and studying the characteristics of the individual gases. The well was the Careunga No. 2, 40 miles north of Moree.

The first flow of water was encountered from 2,466 to 2,540 feet, and was isolated by setting 10-inch casing at 2,630 feet. The second flow, from 2,989 to 3,190 feet, was isolated by setting 8-inch casing at 3,315 feet. The bottom flow, which is the main flow, was found between 3,325 and 3,974 feet. It was intended originally to case off this flow with $6\frac{5}{8}$-inch casing and to proceed to bed rock. Unfortunately the casing parted, and 172 feet was left in the hole. From previous local experience it was not anticipated that any other flows would be found, so that the failure to case off the last (main) flow is not regarded as of vital importance.

The individual gas analyses (Table IX) suggest a progressive increase in nitrogen with depth, a tendency which is general throughout the basin.

At the extreme southwesterly limit of the Great Artesian basin, artesian wells in the northeastern part of South Australia yield considerable quantities of inflammable gas. Thus the Coonanna well, near

TABLE IX

| Constituents | Percentage 1 | 2 | 3 |
|---|---|---|---|
| Carbon dioxide | 0.4 | 0.6 | 0.5 |
| Methane | 83.5 | 44.8 | Nil |
| Hydrogen | 15.7 | 16.5 | Nil |
| Oxygen | Nil | 0.2 | Nil |
| Nitrogen | 0.4 | 37.8 | 99.5 |

1. Upper flow through 10-inch casing.
2. Middle flow through 8-inch casing.
3. Main flow (lowest).

the eastern boundary of the state, burns fiercely and is extinguished with difficulty. Several other wells in the same region exhibit similar phenomena, though the flows are probably less than that at Coonanna.

At the Lake Phillipson well, in the northwestern part of South Australia, and close to the extreme western limit of the Great basin, no gas is reported.

No gas occurs in the Murray Artesian basin, or in the basins of Western Australia.

## NATURAL GAS DERIVED FROM METAMORPHIC ROCKS

There are some interesting occurrences of inflammable gas genetically associated with metamorphosed sedimentary rocks, and with crystalline schists.

At Lobb's Hole copper mine, near Kiandra, in the southeastern part of New South Wales, notable amounts of gas were found. On the assumption that this gas might be derived from petroleum, a well was drilled, but of course no commercial quantity of gas was found, as the gas is derived from incipiently metamorphosed rocks of Silurian age forming the country rocks of a copper lode.

Two analyses of the gas (Table X) from this locality showed that the higher hydrocarbons, hydrogen, carbon monoxide, and sulphuretted hydrogen are absent.[8]

TABLE X

| Constituents | Percentage | |
|---|---|---|
| Carbon dioxide | 5.00 | 4.33 |
| Oxygen | 0.50 | 0.16 |
| Methane | 40.33 | 30.20 |
| Nitrogen | 54.17 | 65.31 |
| | 100.00 | 100.00 |

More interesting is the occurrence of inflammable gas in the deep mines of Kalgoorlie, Western Australia. Natural gas under pressure

[8] J. E. Carne, "Notes on the Occurrence of Coal, Petroleum and Copper in Papua," *Territory of Papua Bull. 1* (1913), p. 77.

has been encountered in several places in the mines of this gold field. The country rock consists of mineralized greenstones and schists of pre-Cambrian age. Graphitic schists are associated with these rocks and it is in their vicinity that the gas is most plentiful.

There would appear to be a direct connection between the gas and the graphite schists, the gas being encountered either actually in such rocks or in fractured rocks close to, and in direct communication with them. This lends support to the theory long held by the writer that the "graphite slates" found in lenticular masses in the heart of large areas of amphibolite and greenstone schist, at Kalgoorlie, Cue, Coolgardie and elsewhere, are in reality shear zones in the greenstone, into which hydrocarbons of volcanic origin have penetrated, depositing finely divided carbon in them during slow combustion. This oxidation may have been at the expense of oxygen in the pores of the rock, or at the expense of ferric compounds capable of reduction to a lower state of oxidation.[9]

Two analyses of the gas were made (Table XI): one of a sample collected in a bag (*1*); the other collected over water in a bottle (*2*). Heavy hydrocarbons are absent.

TABLE XI

| *Constituents* | *Percentage* | |
|---|---|---|
| | *1* | *2* |
| Carbon dioxide | .28 | .33 |
| Oxygen | 5.36 | 7.70 |
| Methane | 56.50 | 42.50 |
| Nitrogen (by difference) | 37.86 | 49.47 |
| | 100.00 | 100.00 |

In direct opposition to official advice, a well has been drilled recently in pre-Cambrian metamorphic rocks in southern Yorke's Peninsula, South Australia, in search for oil. Table XII shows analyses of samples of gas obtained from the well.[10]

TABLE XII

| | *Percentage* | | | | |
|---|---|---|---|---|---|
| *Sample Number* | *1* | *2* | *3* | *4* | *5* |
| Carbon dioxide | 0.8 | 0.2 | 0.8 | 0.8 | 0.6 |
| Oxygen | Nil | Nil | 3.2 | 2.4 | 3.0 |
| Hydrogen | 74.0 | 76.0 | 60.0 | 64.4 | 60.0 |
| Methane | 7.5 | 7.5 | 5.4 | 7.0 | 5.6 |
| Nitrogen | 17.7 | 16.3 | 30.6 | 25.4 | 30.8 |
| | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 |

Samples *1* and *2* from 790 feet; *3* and *5* from 860 feet, contaminated with air.

[9] E. S. Simpson, *Western Australia Geol. Survey Bull. 42*, p. 159.

[10] L. K. Ward, "Half-Year Ending 31st December, 1931," *Review of Mining Operations in South Australia*, No. 55, p. 40.

Carbon dioxide is widespread in association with the older sedimentary formations. Occurrences which may be regarded as typical are the "Soda-Water Spring" near Cooma in southern New South Wales. Carbonic acid gas springs occur at Hepburn, Daylesford, Deep Spring,[11] Eganstown, and Campbelltown, all in Victoria. These yielded 89.2, 88.6, 95.7, and 99.3 per cent of carbon dioxide, respectively.

The Bendigo gold mine at Bendigo, Victoria, yielded gas containing 97.8 per cent of nitrogen.

Volcanic activity, accompanied by sulphur springs and other emanations, at present is confined to the islands. On the mainland of New Guinea,[12] however, no signs of present volcanic activity can be discovered, although there is much evidence of it throughout the Neogene. Sulphur springs ($H_2S$) are abundant, however, and can be found in the rocks ranging from early Paleogene to later Neogene age. Some of the more important are: Upper Mokka River in the Madang district, where the springs occur along the walls of a gorge at intervals in the whole of the length examined, and where they issue from indurated and veined rocks of earlier Paleogene age; near Lupai, inland from Aitape, where the spring issues from unconsolidated sediments of Pleistocene age; and Wanimo, where the outcrop is a limestone of early Neogene age.

### NATURAL GAS PRESUMABLY ASSOCIATED WITH PETROLEUM

During the last quarter of a century there has been more or less activity in the search for oil, which has become intense in later years. This has resulted in the definite discovery of oil in small quantities in the states of Queensland, Victoria, and Western Australia, and in the territories of Papua and New Guinea. Reports, less well authenticated, have been made of similar discoveries in every state in the Commonwealth.

The most definite and extensive development has taken place at Roma, Queensland. Roma is a town in the pastoral belt, 300 miles west of Brisbane, and near the eastern boundary of the Great Artesian basin. In 1900 the second well drilled with the object of supplying the town with water was deepened to 3,683 feet. A strong flow of inflammable gas resulted. Initially, this flow amounted to 39,411 cubic feet per day, but soon increased to 70,000 cubic feet per day. It was allowed to run to waste. In 1906 the town was reticulated, and was supplied with gas for a few days, when the flow suddenly ceased entirely.

[11] Deep Spring and Eganstown are near Daylesford.

[12] *The Oil Exploration Work in Papua and New Guinea Conducted by the Anglo-Persian Oil Company on Behalf of the Government of the Commonwealth of Australia, 1920–1929* (London, 1931). 4 Vols. See Vols. 1–2.

In 1907–08 a third well was drilled less than 100 yards from No. 2. At a depth of 3,702 feet there was a great burst of gas, which ignited and quickly destroyed the steel derrick. It burnt fiercely for 6 weeks, when it was extinguished. Almost immediately afterward the flow ceased because of caving and flooding of the hole.

A fourth well was drilled in 1919 in the immediate vicinity of the other two. Gas was found at 3,705 feet, and, after the well was bailed, a supply was produced estimated at many millions of cubic feet per day. On analysis, this gas was proved to contain gasoline to the extent of 1.25 pints per 1,000 cubic feet. The tools were stuck in the hole, the water encountered at 1,340 feet was not properly shut off, and the well was abandoned.

A private company undertook development operations in quest of oil with up-to-date drilling equipment, and, in September, 1926, found gas at 3,685 feet. After being tested, the well was deepened to 3,703 feet, and a strong flow was obtained. With some intervals of diminution and cessation, the gas flow has been maintained ever since, and has been exploited on a small scale for the extraction of casing-head gasoline by the absorption method.[13]

The analysis of the gas (Table XIII) was made by Professor Steel of the University of Queensland.

TABLE XIII

| *Constituents* | *Percentage* |
|---|---|
| Methane | 87.20 |
| Ethane | 6.03 |
| Propane | 1.34 |
| Butane | 1.62 |
| Inert gases | 3.49 |
| | 99.68 |

An interesting feature of this gas is that helium was recognized in the proportion of 1 in 12,000. In 1928 helium was isolated in recognizable quantities by Professor Coleridge Farr of New Zealand. He found the helium content to be approximately 0.04 per cent.

The pressure of the gas in this well has varied considerably from time to time, closed pressures exceeding 500 pounds per square inch having been recorded. As the casing-head control equipment was not adapted to handling high pressures, it has been necessary to allow a considerable proportion of the gases to escape in order to keep the pressures within limits of safety.

A small absorption plant has been installed at this well. Near the end of 1928 the Minister for Mines in Queensland, E. A. Atherton,

[13] L. C. Ball, *Queensland Govt. Min. Jour.*, Vol. 28 (1927), p. 92.

announced that more than 10,000 gallons (imperial) of gasoline had been recovered to date. At that time the flow amounted to 1,270,000 cubic feet per day, with a gasoline content of 2.6 pints of gasoline per 1,000 cubic feet. Data kindly supplied by the company at present operating the plant indicate that from September 13, 1931, to November 1, 1931, 15,517,075 cubic feet of gas passed through the meter, from which 3,025 (imperial) gallons of gasoline were produced.

In addition to this natural gas, the well at Roma has produced small amounts of very high-grade crude oil, closely analogous with the original crude of Kettleman Hills, California.

These indications of the existence of petroleum have encouraged much speculative drilling in surrounding areas. Such drilling does not compare in intensity or method with American operations under similar conditions, but the results have definitely proved that oil and gas are widespread in the Roma district. No other production approximating commercial quantities has been found. At present there is a possibility that two or more of the wells may become small gas producers.

Table XIV shows analyses from official sources, of some of the gases of this district.

TABLE XIV

| *Sample Number* | *1* | *2* | *3* | *4* | *5* | *6* |
|---|---|---|---|---|---|---|
| Carbon dioxide | 1.7 | 7.0 | 4.0 | 0.6 | 9.1 | 2.1 |
| Air | Nil | Nil | Nil | Nil | Nil | Nil |
| Methane | 85.3 | 88.1 | 92.0 | 76.4 | 72.0 | 89.1 |
| Ethane and higher homologues | 11.4 | | | | | |
| Difference (inert) | 1.6 | 0.4 | 3.1 | 23.0 | 18.9 | 8.8 |
| | 100.0 | 95.5 | 99.1 | 100.0 | 100.0 | 100.0 |

*1.* Well No. 14, P.P.P. No. 100.
*2.* Well No. 4, Blythedale.
*3.* Well No. 5, Blythedale.
*4.* Kawanna well, 326 miles west of Brisbane.
*5.* Longreach oil well.
*6.* Westland No. 3, 44 miles southwest of Longreach.

Undoubted traces of petroleum have been found also at the town of Longreach, 400 miles northwest of Roma. Here, also, the discovery was made in drilling a well to supply the town with artesian water. Small amounts of dark brown paraffine, liquid at the temperature of the water, but solid at air temperature, have been brought to the surface for the past 7 years. In 1929 a well was drilled near the water well in search for oil, but no oil was obtained. Gas and oil showings were reported by the drillers at various places, but the chief indications are found in direct association with the artesian water in the basal beds of the Walloon formation. Gas from this well showed the presence of hydrocarbons other than methane (analysis No. 5 in Table

XIV). Nearly 30 artesian wells in the Longreach district have shown signs of oil, more or less definitely authenticated. So far as is known, however, the previously mentioned gas is the only one in which higher hydrocarbons have been recognized.

Analysis No. 6 in Table XIV is typical of the gases encountered in some of the other wells in the Longreach district, in which traces of oil have been more or less credibly reported.

Noteworthy amounts of crude oil have been obtained from wells near Lakes Entrance in the Gippsland district in the state of Victoria. During the past 2.5 years the aggregate production of water-free oil from this field has amounted to 40,000 (imperial) gallons. Though infinitesimal as commercial production, this recovery of oil indicates the petroliferous nature of the Tertiary rocks in the Gippsland basin, and encourages the belief that, if suitable structure can be located, producing fields may be discovered. For the most part, the amount of gas accompanying the oil in this field is small, though strong short-lived flows have been found.

As shown in Table XV, nothing more than the merest traces of hydrocarbons higher than methane have been recognized in these gases.

TABLE XV

| *Sample Number* | *1* | *2* | *3* | *4* | *5* | *6* |
|---|---|---|---|---|---|---|
| Carbon dioxide | 2.19 | 1.80 | 1.60 | 5.30 | 0.20 | 0.19 |
| Oxygen | 0.40 | 0.20 | 1.20 | 0.30 | Nil. | 0.90 |
| Methane | 94.21 | 56.45 | 26.10 | 82.60 | 81.25 | 93.74 |
| Ethane et cetera | Nil | Nil | Nil | Nil | Nil | Nil |
| Nitrogen | 3.20 | 41.45 | 71.1 | 11.80 | 18.55 | 5.12 |

*1.* Well No. 1, Dumburra, Metung.
*2.* Kalimna Company's Well No. 4, Parish of Colquhoun.
*3.* Well No. 2, Lakes Entrance.
*4.* Nicholson River, Sarsfield.
*5.* Well No. 1, Lake Bunga.
*6.* Well No. 1, Lake Bunga (unsaturated hydrocarbons 0.05 per cent).

Natural gas connected with petroliferous conditions occurs in many localities in the gulf region of Papua.[14] The more important areas in which it has been recorded are: Jokea-Apinaipi, Popo, Hohoro, Kira Hahi, Aipa Hills, and Opau-Ingham Hills.

Mud volcanoes and gas-blows, emitting inflammable gas accompanied generally by brine and in many places by traces of oil, are common in these areas. Nearly all of the mud volcanoes and gas-blows are located on anticlinal structure.

Drilling for oil at Popo and Hohoro was abandoned because of the occurrence at depth of great thickness of bentonite.

[14] *The Oil Exploration Work in Papua and New Guinea Conducted by the Anglo-Persian Oil Company on Behalf of the Government of the Commonwealth of Australia, 1920–1929* (London, 1931). 4 Vols. See Vol. 1.

The writer desires to acknowledge assistance from the officers of State geological surveys, Mines departments, and Water Supply departments in compiling this paper. He is especially indebted to his assistant, Mr. Paul Hossfeld, M. Sc. Owing to the writer's departure, on short notice, for an extended geological expedition, he was compelled to leave the paper in a somewhat unfinished condition, and Hossfeld has supplied the omissions.

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# EN ÉCHELON FAULTS IN OKLAHOMA[1]

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## ABSTRACT

Although formerly postulated general theories of faults in the pre-Cambrian basement rocks and rotational stresses in a horizontal plane appear to be sound for consideration in a study of the *en échelon* faults in eastern Oklahoma, applications of these theories which have been made to regional structure seem unsatisfactory. A westward thrust from the Ouachita Mountains is postulated as the force which created a shearing couple which caused elongation of the faulted area from northeast to southwest, thus causing the development of the northwest trending, *en échelon*, tension faults in belts above north-northeast trending, major shear planes produced in the basement rocks by forces of the couple.

## INTRODUCTION

In the western part of eastern Oklahoma the exposed Pennsylvanian rocks are cut by many short, northwest trending, normal faults which dip northeast or southwest at an average of about 45°. Rarely are the faults as long as 3 miles, and rarely is throw greater than 100 feet. The faults are arranged *en échelon* in belts which trend north-northeast. The buried Nemaha Mountains lie northwest of the faulted area, the Ozark Mountains on the east, the Ouachita Mountains on the southeast, and the Arbuckle Mountains on the south. The faulted area is about 45 miles wide from east to west, and extends from near the Arbuckle Mountains almost to Kansas, a distance of about 125 miles.

Since Fath[3] first studied the origin of the faults, other geologists have contributed additional ideas concerning the problem. Foley[4] has postulated rotational stresses in a horizontal plane, Sherrill[5] has suggested torsion, and Link[6] believes that the belts of faults resulted from

[1] Manuscript received, September 1, 1933.

[2] 606 Eleventh Street.

[3] A. E. Fath, "The Origin of the Faults, Anticlines, and Buried Granite Ridge of the Northern Part of the Mid-Continent Oil and Gas Field," *U. S. Geol. Survey Prof. Paper 128-C* (1920).

[4] Lyndon L. Foley, "The Origin of the Faults in Creek and Osage Counties, Oklahoma," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 10, No. 3 (March, 1926), pp. 293-303.

[5] R. E. Sherrill, "Origin of the *En Échelon* Faults in North-Central Oklahoma," *ibid.*, Vol. 13, No. 1 (January, 1929), pp. 31-37.

[6] Theodore A. Link, "*En Échelon* Tension Fissures and Faults," *ibid.*, Vol. 13, No. 6 (June, 1929), pp. 627-43.

settling over buried ridges. It is probable that *en échelon* faults may be produced according to the tenets of each of the various theories, but the lack of application of the proposed theories to regional structure leaves them equally undemonstrated or of unknown merit.

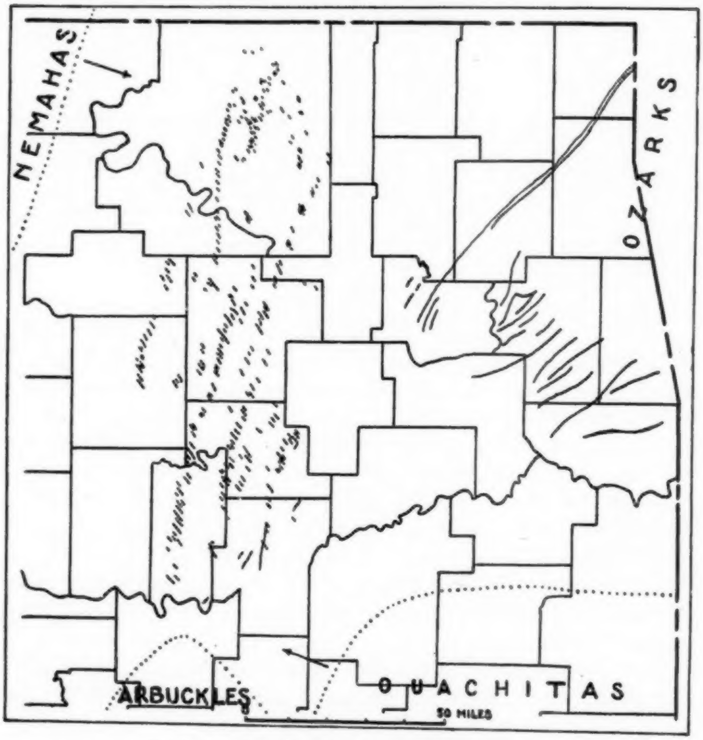


FIG. 1.—Fault map of eastern Oklahoma.

REGIONAL STRUCTURE

In eastern and central Oklahoma north of the Arbuckle and Ouachita mountains and in eastern Kansas, the Carboniferous and Permian formations have a westward inclination which averages about 40 feet per mile. Many or most geologists who have studied the region believe that this dip was imposed upon the strata by absolute uplift in and a westward thrust from the Ozark Mountains. Although the Llano-Burnet uplift is situated southeast of a similarly westward dipping homocline on the east side of the Texas basin, it is usually

concluded that the basin gradually warped down as deposition progressed, and that the dip is depositional. It is probable that the basinward dips in Oklahoma and Kansas and in Texas have had similar origins, and in connection with the theory of absolute uplift in the Ozarks, it might be well to think of the difficulties encountered in attempting to refute Suess'[7] idea that absolute uplift can not take place. Furthermore, an uplift of 10,000 feet or more would have been required to tilt the rocks between the Ozarks and the Anadarko basin from an initial eastward inclination of 15 feet per mile to the present average dip in the opposite direction of 40 feet per mile. Such magnitude of absolute uplift seems unreasonable in view of the present moderate altitude of the region and the probably only slight submergence of each bed during its deposition.

In late Mississippian and early Pennsylvanian time the Nemaha Mountains were uplifted along a north-northeast line which, if projected northward from its known position in Pawnee County, Nebraska, merges with the similarly trending Killarnean axis of pre-Cambrian rocks which crop out in Minnesota. The parallelism of the belts of *en échelon* faults with the Nemaha ridge strongly suggests that the grain of the pre-Cambrian rocks underlying most of eastern Oklahoma is north-northeast. Since its origin, the pre-Cambrian grain has probably played a large part in the determination of structural and physiographic trends. Valleys, ranges, and structural axes, and hence depositional strikes, have probably been controlled by it.

The major orogeny in the Arbuckle Mountains, approximately contemporaneous with that in the Nemahas, occurred prior to the deposition of at least some of the beds which are cut by the *en échelon* faults.

As pointed out by Miser,[8] there is no profound reason for dating the Ouachita orogeny more precisely than between Allegheny and Cretaceous time. That is, it may have occurred after the deposition of the youngest beds which are cut by *en échelon* faults. Many geologists believe that the Ouachitas were thrust far toward the north by forces directed from the south or southeast, and that these same stresses strained the rocks far north of the mountains. However, only the north flank of the fold belt is well exposed, the south flank being concealed under the sediments of the Gulf Coastal Plain, and criteria exclusively from the north flank have been used as indicators that pres-

[7] Edouard Suess. Explained in: Bailey Willis and Robin Willis, *Geologic Structures* (New York, 1929), p. 87.

[8] Hugh D. Miser, "Structure of the Ouachita Mountains of Oklahoma and Arkansas," *Oklahoma Geol. Survey Bull. 50* (1929), p. 27.

sure was directed from the south. Folds in the Choctaw anticlinorium in McCurtain County, Oklahoma, on the south flank of the mountains are overturned toward the south, and thus afford evidence that the Ouachitas represent a sector which has been, in effect, underthrust by stresses directed from the north and from the south. The short distance in which folding dies out on the north flank of the mountains, also substantiates this suggestion. This theory that folding of the Ouachitas was caused by pressures both from the north and from the south is more in accord with the idea that the earth's crust is not competent to transmit stresses for great distances.

## ANALYSIS OF THEORIES

Fath's theory that the north-northeast trending belts of faults were formed by subsurface rifts in the pre-Cambrian rocks under the belts has had many adherents. A northward thrust[9] from the Ouachitas, if transmitted into the area of *en échelon* faults, may have produced the postulated northward movements on the east sides of the rifts, but the dying out of Ouachita folding far toward the southeast of the faulted area casts doubt upon this source of thrust.

Foley attempted to explain these postulated rifts in the basement rocks as being the result of rotational stresses in a horizontal plane set up by a westward thrust from the Ozark uplift, with resistance by the Nemaha ridge supplying the eastward stress of the couple. Elongation in the northeast-southwest directions, resulting from these stresses, is considered as the cause for the northwest trends of the presumably tension faults. The general theory of rotational stresses is very appealing, but as it is not demonstrated that uplift in the Ozarks produced the regional westward dip and exerted a westward thrust, and as such a thrust would have caused strain near the center, not at the south end, of the faulted area, it appears that a westward thrust from the Ozarks is inadequate to account for the belts of faults. If the postulated thrust from the Ozarks had actually taken place and had caused the faulting, would not the faults in the southern part of the area have northeast trends in north-northwest trending belts, because elongation northwest and southeast should have resulted from rotational stresses resulting from the postulated thrust from the Ozarks coupled with resistance from the Arbuckles?

Torsion as applied in the laboratory can produce *en échelon* faults, but it is doubtful that the twisting of glass and cake frosting is analogous to torsion in these less brittle, faulted rocks. It is probable that

[9] John W. Merritt and O. G. McDonald, "Oil and Gas in Creek County, Oklahoma," *Oklahoma Geol. Survey Bull. 40-C* (1926), p. 28.

the amounts of torsion as applied in experiments are much greater than any twisting which might have affected the faulted area, and of course, experiments cannot take into account recuperation from fatigue during rest from torsion of the rocks. If it be granted that all of the westward inclination of the faulted beds was produced by uplift subsequent to deposition, the ratio of uplift to horizontal distance probably would not be greater than 1 to 100.

It is conceivable that belts of *en échelon* faults might develop in brittle rocks during intense settling over buried ridges, but as has been pointed out by Sherrill,[10] if the faults were formed in this manner, why should all of the faults in all of the belts have the same northwest trends? Should not some of the faults bear north-northeast while others trend northwest?

### ELONGATION IN OUACHITA SECTOR

Much has been written of the north-south shortening of the earth's crust in the Ouachita Mountains, but little has been said of the east-west elongation which must have accompanied the shortening. The offset folds in the pre-Carboniferous rocks in Black Knob Ridge at the west end of the Ouachitas indicate that westerly directed stresses accompanied the folding, and doubtless a tendency toward elongation was felt throughout the entire length of the mountains and in the buttress elements between which the fold belt was compressed. The basement rocks in the buttresses may have been strained by elongation in areas far removed from the Ouachita folding.

### WESTWARD THRUST FROM OUACHITAS

With resistance from the Nemaha ridge as one force, as proposed by Foley, the westward thrust caused by elongation in the Ouachitas may have produced a shearing couple which strained the area of *en échelon* faults.

In rock stressed by a couple most shearing takes place[11] parallel with that plane of no distortion which intersects the lines of the forces with acute angles pointing towards the directions of push. In the case of this Nemaha-Ouachita couple, this plane of maximum shear almost precisely corresponds to the plane of the probable grain in the pre-Cambrian basement rocks. Shearing would have been unusually facilitated along this grain so that much of the pressure of elongation in the Ouachitas may have been dissipated by this shearing. Shearing

[10] R. E. Sherrill, "Origin of *En Échelon* Faults" (a discussion of Link's paper), *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 13, No. 10 (October, 1929), p. 1398.

[11] Bailey Willis and Robin Willis, *Geologic Structures* (New York, 1929), p. 234.

along the pre-Cambrian grain may have been so facile that displacements may have occurred as far north as southernmost Kansas.

### TRENDS OF FAULTS AND THEIR BELTS

Movements along these postulated shears or faults in the basement rocks would have been toward the south on their east sides. Therefore, according to the experiments of Fath, it seems that the faults in the exposed rocks should have northeast trends rather than their actual northwest trends, but due to the elongation of the area from northeast to southwest, northwest trending tension faults would have developed. Probably only minor horizontal displacements would have occurred along the deep-seated shear planes, but the aggregate shearing would have caused elongation from northeast to southwest and shortening from northwest to southeast. The belts of faults are probably located above major shear planes along which greater vertical or horizontal displacements occurred.

The northeast trending normal faults of eastern Oklahoma may be grain shears or faults which proceeded upward into the younger rocks from the pre-Cambrian basement.

### DISCUSSION

ROBERT H. DOTT, Tulsa, Oklahoma (written discussion received, October 2, 1933): The idea that the Ozark uplift caused the regional west dip of the Prairie Plains homocline was formerly held almost universally by Mid-Continent geologists, and is still believed by many. The literature on Oklahoma geology is full of such references.

Mr. Kramer states that ". . . it is not demonstrated that uplift in the Ozarks produced the regional westward dip. . . ." It not only has not been demonstrated, but the regular strike of the post-Cherokee members of the Pennsylvanian from the Central Mineral area of Texas, to Iowa, shows rather definitely that the Ozarks had no part in producing the Prarie-Plains homocline.

The map of the Pennsylvanian area of the Mid-Continent region published by Plummer and Moore,[12] shows beyond much question that the mountain uplifts have had little or no effect on the regional structure of the Pennsylvanian of the Mid-Continent, and that the origin of the Prairie-Plains homocline is more probably bound up in the problem of continental structure, perhaps related to the Appalachian revolution.

LYNDON L. FOLEY, Tulsa, Oklahoma (written discussion received, December 5, 1933): The regional structure of the Mid-Continent area is definitely related to the structure pattern of the southeastern part of the North American continent. The Appalachian Mountains, the Cincinnati and Nashville

[12] F. B. Plummer and R. C. Moore, "Stratigraphy of the Pennsylvanian Formations of North-Central Texas," *Univ. Texas Bull. 2132* (1921), Pl. 26, p. 207.

R. C. Moore, "The Relation of Mountain Folding to the Oil and Gas Fields of Southern Oklahoma," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 5, No. 1 (January–February, 1921), p. 47.

arches, the southeast extension of the Ozark Mountains, and the Ouachita overthrust were caused by compressive stresses from the southeast. A general positive area extends from the Ozarks to the Llano-Burnet area and the different mountain areas represent peaks along this positive area. In the immediate vicinity of each mountain area, the Pennsylvanian beds correspond perfectly with the mountain structure. West of these mountain areas, the attitude of the Pennsylvanian beds is determined by the general positive area and is less influenced by the individual peaks along this positive area. This so-called positive area separates the great Plains basin from the Mississippi Valley basin and is a general expression of the forces from the southeast which have deformed this area.

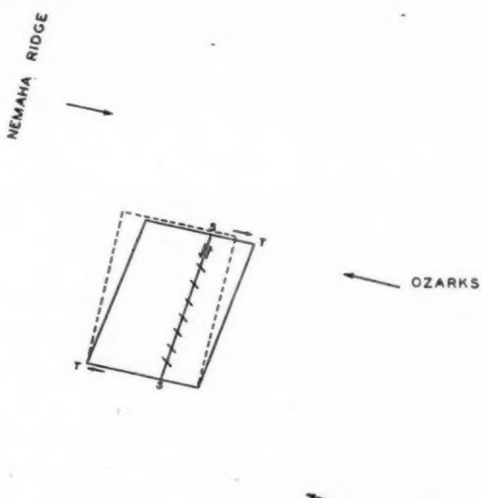


FIG. 2

The western margin of the Ouachitas near Atoka is sharply folded and thrust faulted which favors Miser's conception of compression from the southeast rather than Kramer's suggestion of north-south compression with westward elongation. The effect of westward thrusting from the Ouachitas, in producing *en échelon* faults, was suggested in my paper referred to by Kramer. The importance of the Ouachita deformation was emphasized by Thom and Ickes in their discussion of my paper. A thrust from the Ouachitas, or from both the Ozarks and the Ouachitas, would be adequate to explain the *en échelon* fault zones.

Mr. Kramer states, in his paragraphs headed "Trends of Faults and Their Belts," that the movement along these postulated shears or faults in the basement would have been toward the south on their east sides. I believe this statement is an error in mechanics. Figure 2 shows a strain diagram illustrating the deformation involved. A rectangular element is indicated by

dashed lines and the deformed element by solid lines. *TT* is the axis of elongation and *SS* is a line of shear. The movement along the shear line is northward on the east side. The *en échelon* fractures resulting from such a movement would be normal to the axis of elongation as indicated in the sketch. The trends of these *en échelon* fractures are the same as the trend of the *en échelon* faults of Oklahoma.

William Kramer, (written discussion received, January 22, 1934): As apparently demonstrated by the experiments of Fath, movements northward on the east sides of basement rifts could have produced northwest trending faults in the overlying rocks. However, if a westward thrust from the Ouachitas actually constituted the more active force of the couple which produced the belts of faults, would not the acute angles (between the force and the basement rift planes) have overridden the obtuse angles as in the case of thrust faults? Thus, if there have been horizontal movements along buried rifts, the writer is of the opinion that such movements were southward on the east sides.

BULLETIN OF THE AMERICAN ASSOCIATION OF PETROLEUM GEOLOGISTS
VOL. 18, NO. 2 (FEBRUARY, 1934), PP. 251-262, 10 FIGS.

# TECTONICS OF OKLAHOMA CITY ANTICLINE[1]

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ABSTRACT

The Oklahoma City anticline is an elongate domed anticline trending N.30°W. The axis of folding shifts eastward with depth and the pre-Pennsylvanian beds are strongly faulted on the eastern side of the fold. The forces which caused the deformation have been periodic and recurrent. They are shown to be definitely related to orogenic forces which have deformed the North American continent.

The purpose of the writer is to present the results of a study of the structure of the Oklahoma City anticline as revealed by drilling. The stages of its growth at different times were studied and an attempt is made to explain the forces which produced the structure

The writer is greatly indebted to Frederic A. Bush and Robert M. Whiteside for assistance without which this paper could not have been written.

The surface and subsurface stratigraphy of the Oklahoma City area have been discussed exhaustively elsewhere and are not dealt with here. The beds involved range from the Arbuckle limestone of Cambro-Ordovician age, to the Garber sandstone and Hennessey shale of the Permian system exposed at the surface. The general section, according to McGee and Clawson, is shown in Figure 1.

The Oklahoma City anticline is situated in Ts. 10, 11, and 12 N., Rs. 2 and 3 W., Cleveland and Oklahoma counties, Oklahoma. The structure, as mapped on the surface beds, is shown in Figure 2. The structure shown at the surface is an elongate domed anticline having about 90 feet of closure. The axis trends N. 30 W. The high point of the surface dome is near the southeast corner of Sec. 24, T. 11 N., R. 3 W. The steeper dip is on the east side of the anticline. The structure of the Checkerboard limestone, at a depth of about 5,200 feet, is shown in Figure 3. The axis of the structure of the Checkerboard limestone has the same trend as the anticline in the surface beds but has shifted 0.75 mile east. The dips are steeper than in the surface beds and the east dip is very steep. The structure of the Arbuckle limestone, or "Siliceous lime," at a depth of 6,100–6,500 feet, is shown

[1] Read before the Association at the Oklahoma City meeting, March 24, 1932. Revised manuscript received, October 24, 1933.

[2] Geologist, Mid-Kansas Oil and Gas Company.

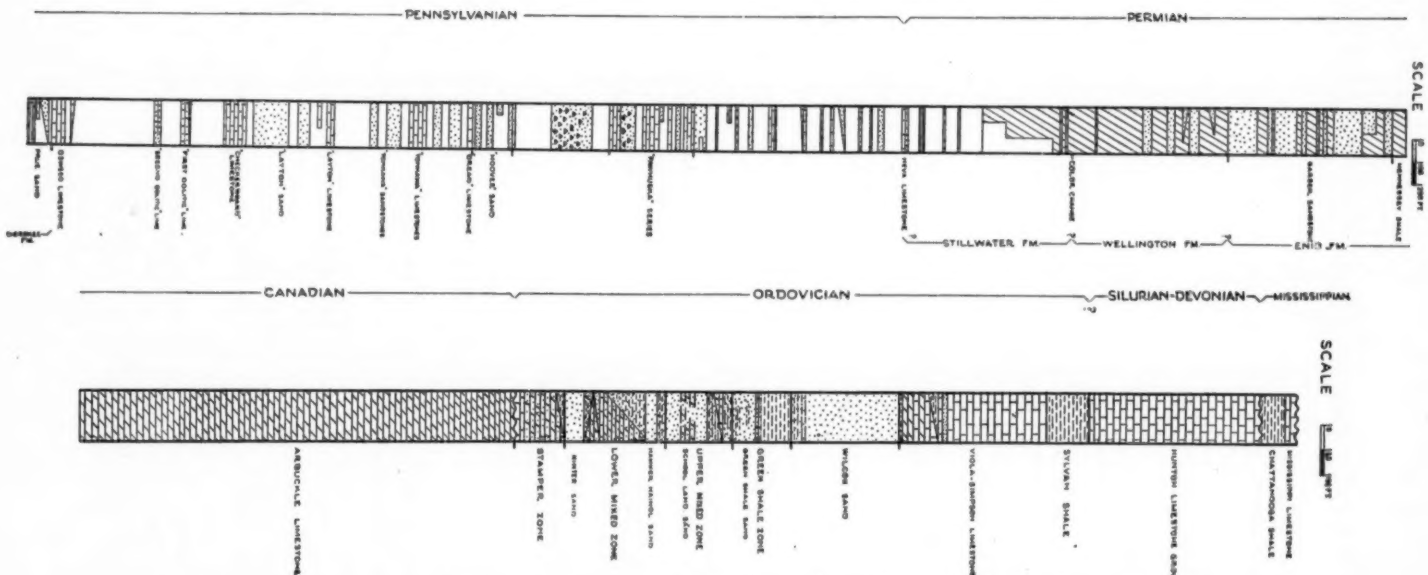


FIG. 1.—Generalized columnar section of Oklahoma City field. From McGee and Clawson, "Geology and Development of Oklahoma City Field, Oklahoma County, Oklahoma," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 16, No. 10 (October, 1932), p. 966.

in Figure 4. The folding is much sharper than in the higher beds, the axis is shifted farther east and the anticline is sharply faulted on the eastern side.

The progressive eastward shifting of the axis of the fold is shown in Figure 5. The eastward dip of the axial plane of the fold is approxi-

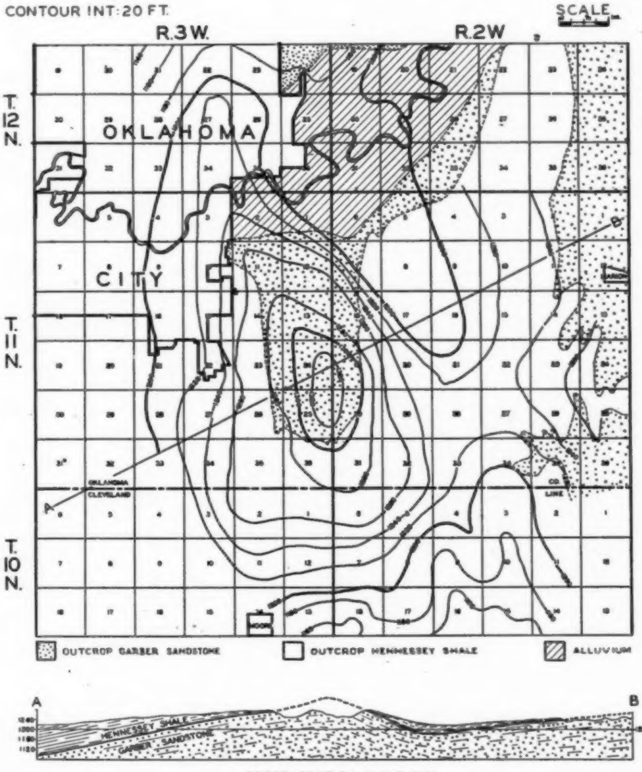


FIG. 2.—Oklahoma City anticline as mapped by Indian Territory Illuminating Oil Company. From McGee and Clawson, "Geology and Development of Oklahoma City Field, Oklahoma County, Oklahoma," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 16, No. 10 (October, 1932), p. 962.

mately 53°. The Oklahoma City anticline is situated on the east side of the Anadarko basin, and the beds on the east dip eastward to a minor syncline and then rise eastward toward the Hunton arch and the Ozark uplift. The axial plane of the fold dips toward the uplift in

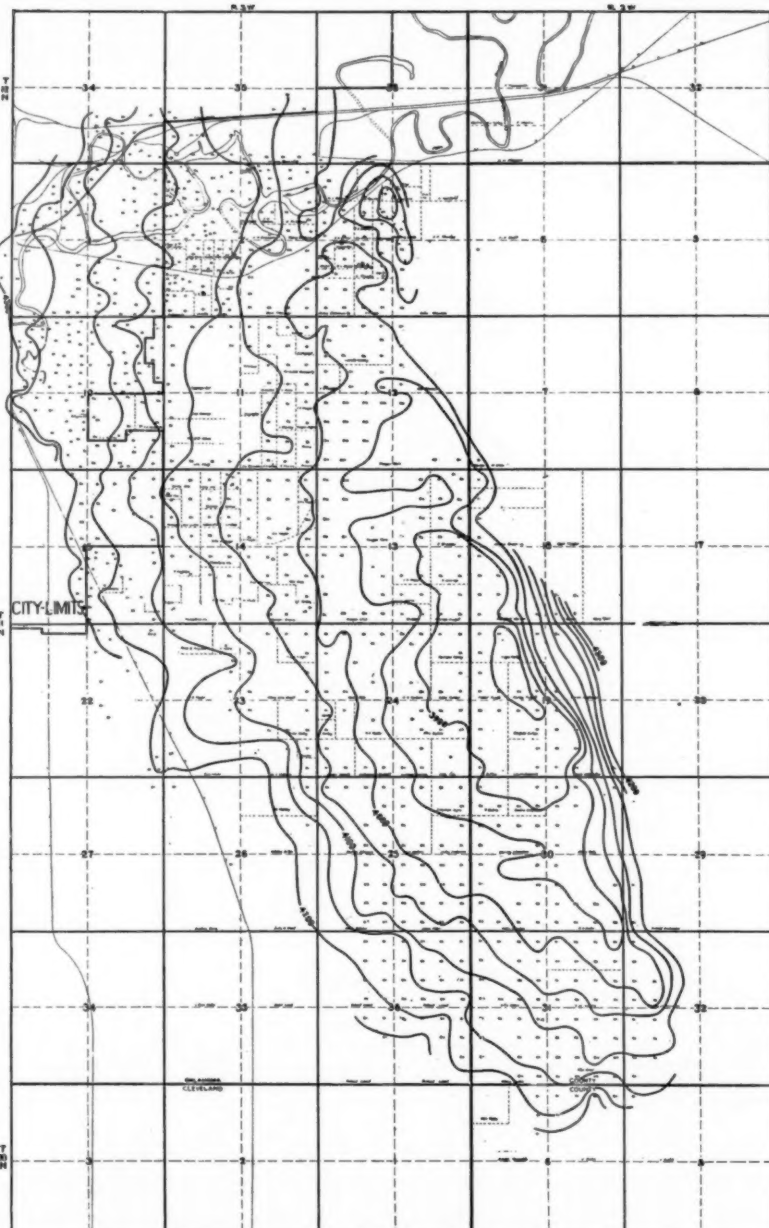


FIG. 3.—Structure of Oklahoma City anticline as mapped on Checkerboard limestone. From McGee and Clawson, "Geology and Development of Oklahoma City Field, Oklahoma County, Oklahoma," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 16, No. 10 (October, 1932), p. 987.

contrast to the folds of Osage and Creek counties, in which the axial planes dip away from the uplift.

A west-east section across the field is shown in Figure 6. This cross section shows the truncation of the pre-Pennsylvanian anticline and a fault of about 2,000 feet displacement which cuts the lower beds on the eastern side of the anticline. The higher beds dip east on the

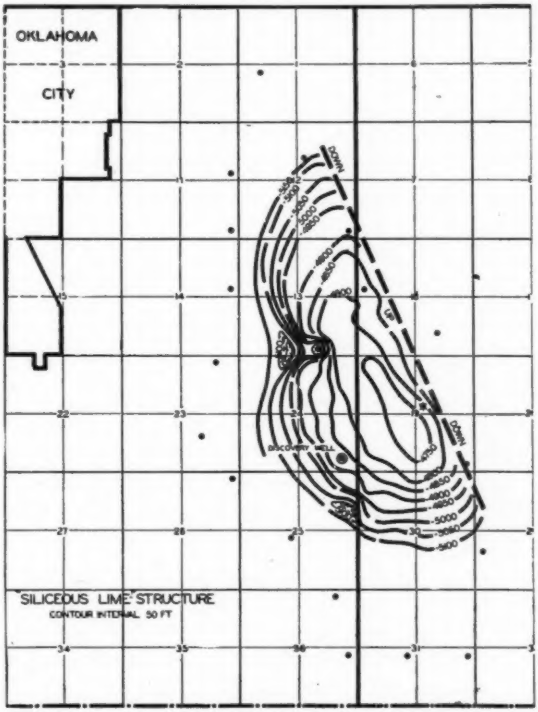


FIG. 4.—Structure of Oklahoma City anticline, as mapped on Arbuckle limestone. From Homer H. Charles, "Oklahoma City Oil Field, Oklahoma," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 14, No. 12 (December, 1930), p. 1529.

eastern side of the axis but apparently are not faulted. The highest point on the Pawhuska limestone shown in this section is in well No. 5, and the highest point on the Oswego limestone is in well No. 6, which also illustrates the eastward shift of the axis. Figure 7 shows two sections across the fault. As the vertical and horizontal scales are the same, there is no distortion in the representation of the structure. The

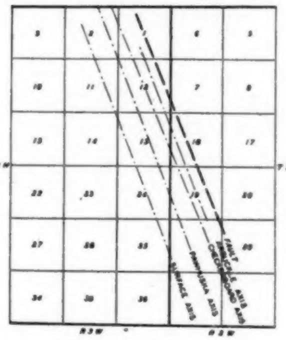


FIG. 5.—Sketch map showing position of axis of anticline on different key horizons and showing eastward shift of axis on deeper beds.

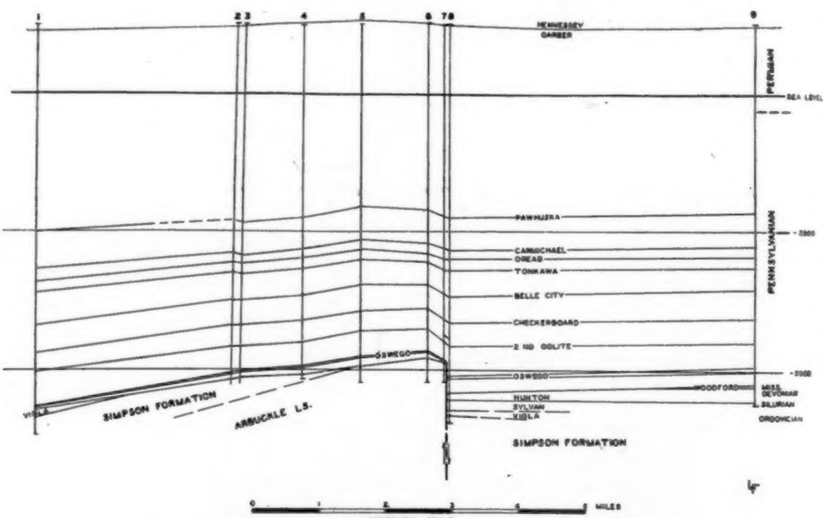


FIG. 6.—West-east section across Oklahoma City anticline. Wells used in section are as follows.

| | |
|---|---|
| 1. Warr, Castle No. 1 | SW., SW., NW., Sec. 20, T. 11 N., R. 3 W. |
| 2. Kessler, Canning No. 1 | SE., SE., SE., Sec. 22, T. 11 N., R. 3 W. |
| 3. Shell-Phillips, Egermier No. 1 | SW., SW., SW., Sec. 23, T. 11 N., R. 3 W. |
| 4. Mid-Kansas, Mollman No. 1 | SE., SE., SE., Sec. 23, T. 11 N., R. 3 W. |
| 5. I.T.I.O., Fortson No. 1 (discovery) | Cen., SE., SE., Sec. 24, T. 11 N., R. 3 W. |
| 6. Shell, Petty No. 6 | NE., NW., NE., Sec. 30, T. 11 N., R. 2 W. |
| 7. Shell, Petty No. 3 | NE., NE., NE., Sec. 30, T. 11 N., R. 2 W. |
| 8. Prairie-Slick, Hiddleson No. 2 | SE., SE., SE., Sec. 19, T. 11 N., R. 2 W. |
| 9. Ryan Consolidated, Lawton No. 1 | NE., NE., NW., Sec. 3, T. 11 N., R. 2 W. |

sections indicate that the fault probably extends upward into the Oswego limestone but possibly not into the higher beds. The dip of the fault plane is unknown. Figure 7-*A* shows that the dip of the fault plane must be very steep if the fault is normal. The fault may be a vertical shear plane, or, so far as our information shows, the fault plane may dip west, forming a reverse or thrust fault. Figure 7-*B* shows that the fault plane, if the fault is normal, must have a steep dip. It shows also the Mississippian beds on the east side of the fault

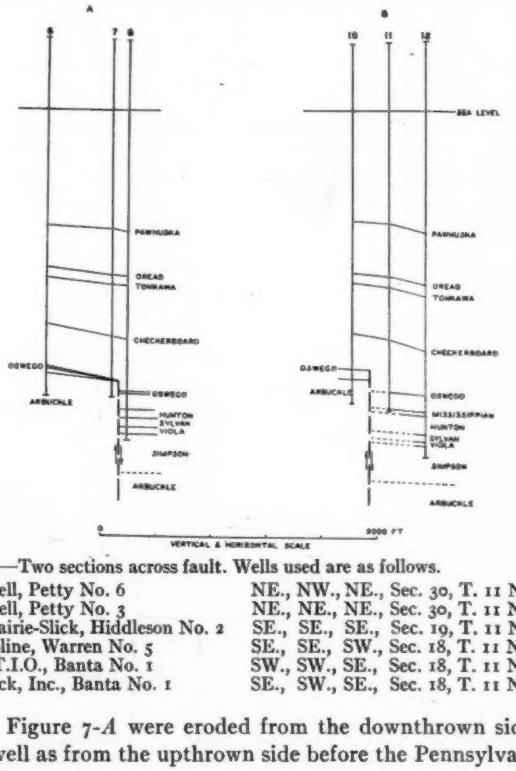


FIG. 7.—Two sections across fault. Wells used are as follows.

| | |
|---|---|
| 6. Shell, Petty No. 6 | NE., NW., NE., Sec. 30, T. 11 N., R. 2 W. |
| 7. Shell, Petty No. 3 | NE., NE., NE., Sec. 30, T. 11 N., R. 2 W. |
| 8. Prairie-Slick, Hiddleson No. 2 | SE., SE., SE., Sec. 19, T. 11 N., R. 2 W. |
| 10. Coline, Warren No. 5 | SE., SE., SW., Sec. 18, T. 11 N., R. 2 W. |
| 11. I.T.I.O., Banta No. 1 | SW., SW., SE., Sec. 18, T. 11 N., R. 2 W. |
| 12. Slick, Inc., Banta No. 1 | SE., SW., SE., Sec. 18, T. 11 N., R. 2 W. |

which in Figure 7-*A* were eroded from the downthrown side of the fault as well as from the upthrown side before the Pennsylvanian was deposited.

Very little is known of the pre-Pennsylvanian deformational history of this fold. No Mississippian, Devonian, or Silurian rocks, and only a thin section of the Ordovician are present over the top of the anticline. Comparatively few wells have been drilled through these beds on the flanks of the anticline. The pre-Pennsylvanian history must be inferred from our knowledge of regional geology.

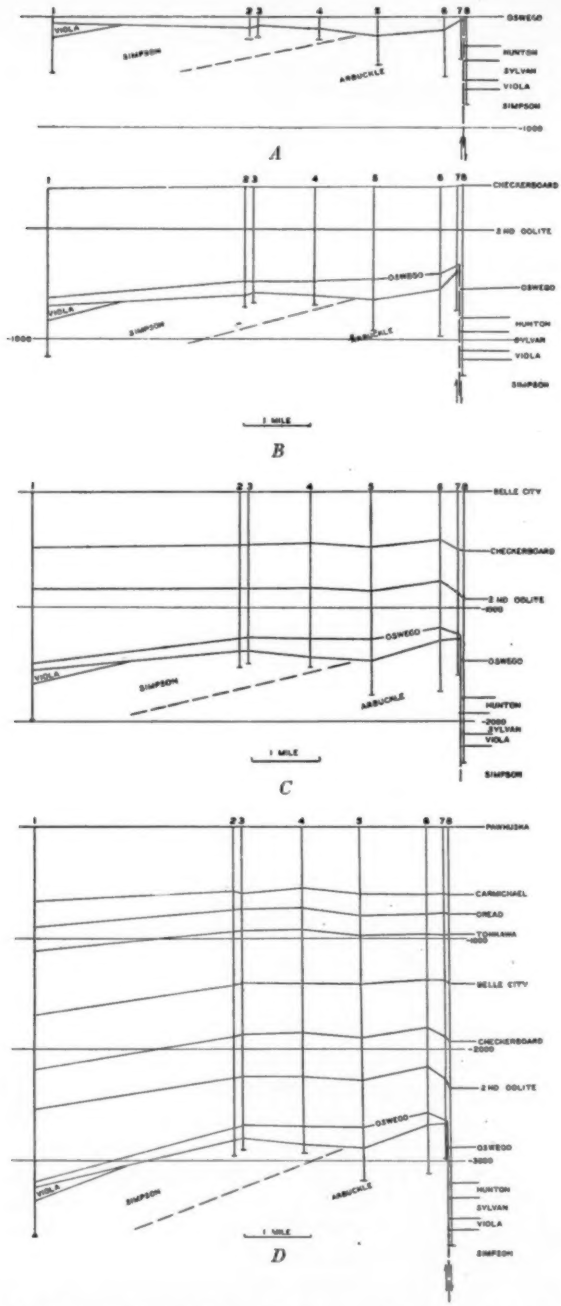


FIG. 8.—Cross sections showing conditions at various stages of development of Oklahoma City anticline.

*A*—Time of Oswego deposition.
*B*—Time of "Second oölite" and Checkerboard deposition.
*C*—Time of Belle City deposition.
*D*—Time of Pawhuska deposition.

The deformational history of Pennsylvanian and later time may be determined from the series of cross sections shown in Figure 8. The conditions at the time of Oswego deposition are shown in Figure 8-*A*. The Oswego limestone is used as a datum bed and the section shows the attitude of the lower beds at the time the Oswego was deposited horizontally. At the beginning of Pennsylvanian deposition, the fold was well developed and the fault had a vertical displacement of about 2,000 feet, with an eastward facing escarpment about 250 feet high. The surface of the lowland on the east was Hunton limestone which was faulted down against the Arbuckle. The Mississippian beds and part of the Hunton were eroded from the area immediately east of the fault, although, as shown in Figure 6 and Figure 7-*B*, Mississippian beds are present northward and eastward from this point. The Arbuckle surface on the western side of the fault sloped west into a valley below the Arbuckle-Simpson contact which cropped out in the higher ground west of the valley. The Simpson and Viola outcrops formed higher land on the west side of this valley. The advancing Pennsylvanian sea first flooded the lowlands east of the scarp, then rose into the valley west of the scarp, and finally submerged the ridge along the scarp and the high land west of the valley just before the Oswego was deposited.

The conditions when the "Second oölite" and Checkerboard limestone were deposited, are shown in Figure 8-*B*. After the deposition of the Oswego limestone, and before the "Second oölite" was deposited, movement took place along the fault and the Oswego was evidently displaced 225 feet. The sharp upturn of the Oswego and the Arbuckle limestones on the west side of the fault is strongly suggestive of reverse faulting. A westward tilting of the area shown in the western part of the section took place during the same interval. Between the deposition of the "Second oölite" and the deposition of the Checkerboard limestone, there was almost a complete quiescence excepting for a slight movement along the fault.

Conditions at the time of the deposition of the Belle City or "Layton" limestone are shown in Figure 8-*C*. There was no appreciable movement in the western part of the area between the time when the Checkerboard was deposited and the deposition of the Belle City limestone, although pronounced folding took place immediately west of the fault. The Oswego limestone, which dipped sharply westward away from the fault at the time of Checkerboard deposition, dipped sharply eastward toward the fault, at the time the Belle City was deposited.

Conditions at the time of Pawhuska deposition are shown in Fig-

ure 8-*D*. Between Belle City time and Tonkawa time, westward tilting took place in the western part of the area. Some movement took place along the fault as is shown by the dip of the Belle City between wells 7 and 8. Between Tonkawa time and Carmichael time, slight westward tilting took place on the western side of the anticline, but there was no appreciable movement above the fault. This interval was a time of relative quiescence. Folding took place following Carmichael deposition and a distinct anticline was present in the Carmichael and Tonkawa beds when the Pawhuska formation was deposited.

Referring again to Figure 6, it is seen that additional folding movements took place between Pawhuska time and the beginning of Hennessey time. The exact time or times of this movement can not be determined definitely in this area because of the lack of detailed well log data in the upper part of the section, but the dips are distinctly steeper in the Pawhuska than in the surface beds. The present structure of the surface beds shows the amount of folding which has taken place since Hennessey time.

The deformational history of the Oklahoma City anticline as revealed by a study of the well logs may be summarized as follows. In Cherokee time a well developed, faulted anticline was already present in the older beds. This anticline was deeply truncated, with the Mississippian, Devonian, Silurian, and a considerable thickness of the Ordovician beds eroded from its crest. The fault on the eastern side of the anticline had a displacement of about 2,000 feet and the Arbuckle limestone formed an escarpment approximately 250 feet high on the western side of the fault. The advancing Pennsylvanian sea flooded the low land on the east, rose over the truncated anticline and submerged it completely shortly before the Oswego limestone was deposited. Deposition continued with alternating intervals of movement and quiescence. Notable displacement took place along the fault shortly after Oswego time, then only slight movement until Belle City time, and no appreciable movement thereafter. In the first post-Oswego movement, the Oswego limestone was turned sharply upward toward the fault, which suggests reverse or thrust faulting. The movement from this time until Belle City time consisted of folding and slight movement along the fault, while folding was dominant after Belle City time.

Figure 9 shows an analysis of the stresses which might produce such a structure as the Oklahoma City anticline. *A* shows simple compression; *B* and *C* show simple rotational stresses, both sets of stresses causing the same deformation; *D* shows rotational deformation caused by non-parallel stresses. It is necessary to examine the deformational

structural history to determine which combination of stresses most probably caused the folding at Oklahoma City.

The regional history of the Mid-Continent area has been discussed by Powers,[3] van der Gracht,[4] and many others. Powers says:

> The origin of the Plains type of folding is essentially recurrent folding at several periods, the loci of movement being the same. Tangential compression was transferred through the basement crystalline rocks and transmitted from them into the overlying sediments.

He says that the region was uplifted as early as Mississippian time; that the Ouachita folding occurred in early Pennsylvanian (Atoka)

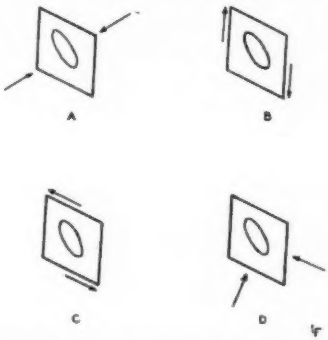


FIG. 9.—Strain diagrams showing stresses which might cause such folds as Oklahoma City anticline.

*A*—Simple compression.

*B* and *C*—Simple rotational deformation.

*D*—Rotational deformation caused by non-parallel stresses.

time contemporaneous with folding in the Arbuckle Mountains. Overthrusting in Seminole time was caused by forces from the southeast. He describes shortening of the entire region by compression from the south and says that folding and warping were spasmodic but frequent throughout Pennsylvanian and Permian time.

The eastern part of the North American continent has been subjected periodically to compressive stresses acting in a direction N. 45°W. These stresses have been recurrent from early Paleozoic to post-

[3] Sidney Powers, "Structural Geology of the Mid-Continent Region: A Field for Research," *Bull. Geol. Soc. Amer.*, Vol. 36 (1925), pp. 379–92.

———, "Age of the Folding of the Oklahoma Mountains; the Ouachita, Arbuckle and Wichita Mountains of Oklahoma and the Llano-Burnet and Marathon Uplifts of Texas," *Bull. Geol. Soc. Amer.*, Vol. 39 (1928), pp. 1031–72.

[4] W. A. J. M. van Waterschoot van der Gracht, "Permo-Carboniferous Orogeny in South-Central United States," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 15, No. 9 (September, 1931), pp. 991–1057.

Tertiary time. They have caused severe deformation along the eastern side of the continent. The present structure of the Appalachian mountains represents the total deformation caused by all of these periods of recurrent stresses. The Mid-Continent area has been subjected periodically to the same stresses. In the Mid-Continent area also, these stresses have been recurrent throughout our geological history. The southwest extension of the Ozarks in Oklahoma, the oil-producing folds in Muskogee County, the Billings anticline, the southwest extension of the Tonkawa anticline and many other structural features of the Mid-Continent have the same trend as the Appalachians, have suffered the same history of periodic compression from the southeast

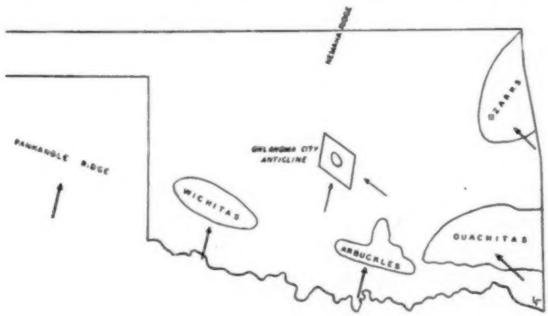


FIG. 10.—Sketch showing application of forces of regional deformation to problem of Oklahoma City anticline.

and may be attributed to the same tectonic forces which have folded the Appalachians.

The southern part of the North American continent has been deformed also by compressive stresses acting in a direction about N. 15°E. Lines of deformation in the Greater Antilles, mountains in the Isthmus of Tehuantepec, Guatemala and Honduras, the Concho divide and the Panhandle ridge of Texas, the Arbuckle and Wichita mountains of Oklahoma and the Chautauqua arch of Kansas, are examples of structural features caused by this system of stresses.

It is suggested that forces from the southeast acting contemporaneously with forces from the southwest, as described by Powers, would cause the type of deformation illustrated in Figure 10, and in Figure 9-*D*. It is therefore concluded that the Oklahoma City anticline is a result of the combined effect of the two great systems of forces which have deformed the southern and eastern portions of the North American continent.

BULLETIN OF THE AMERICAN ASSOCIATION OF PETROLEUM GEOLOGISTS
VOL. 18, NO. 2 (FEBRUARY, 1934), PP. 263-265

# GEOLOGICAL NOTES

## AN EXPLANATION FOR LARGE AMOUNTS OF GAS IN ANDERSON AND LEON COUNTIES, TEXAS

Our knowledge of the several fundamental processes of oil and gas formation and accumulation is mostly limited to theories. There are surprisingly few proved facts. It is remarkable to consider how little we actually know about the formation of oil or gas; where it comes from, how it migrated, and even whether it necessarily migrated. It is generally considered desirable to drill structures that were folded before oil and gas accumulation, but in many cases, the time of accumulation in relation to folding, is unsusceptible of proof.

Since so few facts are really known regarding source and accumulation, the writer may be forgiven if he attempts to explain the recent developments in Anderson and Leon counties, Texas, by adding to the already top-heavy pile of theories.

At the present writing (January 15, 1934) the Tidal-Seaboard have drilled three wells on their Long Lake structure. A well defined anticline exists, but so far, it has yielded large amounts of gas and relatively small amounts of oil in the Woodbine horizon. In Leon County, the Shell *et al.*, have drilled two wells to the Woodbine, the first showing small amounts of gas and oil with much water, the second, and higher well, producing only gas and distillate. A third well is being drilled between the two, in the endeavor to find oil below the gas. It is interesting to speculate on why such a condition exists when only 55 miles northeast lies the East Texas field,[1] which is well known for its low gas content, excepting in the southern part, where gas is predominant. The Van field is 60 miles north and has a small amount of gas with its oil excepting in one small area.

If a line is drawn from the southern end of the Woodbine sand, on the outcrop, to its southern end, along the Mexia fault zone, and projected eastward as indicated there, it will not miss the Leon County pool very far. Theoretically, therefore, before the Shell drilled Phillips No. 1, one would have expected a very thin section of Woodbine. Instead, there was approximately 400 feet. This 400 feet, however, was not similar to the Woodbine of the East Texas field or the fault-line fields, but was mainly shale with thin intercalated sands, poor

[1] Boggy Creek salt dome, which produced both gas and oil, is less than 30 miles northeast of the Long Lake, structure, above referred to.

sands, and sandy shales. The Anderson County wells contained a better sand section.

In the Association *Bulletin* of January, 1923, page 67, J. Claude Jones wrote an article in which he concluded from studies of the sediments of the old Lake Lahontan Valley that beds deposited under fresh water tended to contain no oil or oily residue, because of slow decay. As the lake became salty, the type of decay producing bacteria changed and oil resulted. Possibly the salt water had something to do with this change. Gas is the first product of decay, and with deposition under fresh or slightly brackish water, one might expect a predominant amount of gas as the end product of bacterial action.

If we theorize as follows, we reach a conclusion that is not illogical and explains all the known facts. Suppose we imagine the Woodbine sea as having its northen border in southern Oklahoma and Arkansas, from which it received most of its sand. Its eastern shore was on the west side of the Sabine uplift, which contributed some of the sand. On the south, it was bounded by a low land mass capable of supplying much mud but only little sand—all laid down under fresh or brackish water. The presence of this land mass is suggested by a zone of east and west striking faults, most of them with the downthrow on the north, lying in southern Rusk, central Cherokee, and southeastern Anderson counties. A further corroboration lies in the absence of known salt domes in an east-west band of counties from the Louisiana line westward, separating the interior salt domes from the coastal salt domes.

If this land mass existed, and if Jones was correct in his belief, we are justified in the assumption that structures in the southern part of the East Texas basin contain relatively large amounts of gas and little oil, and the proportions vary with the position of the pool in relation to our land mass.

The writer realizes that a conclusion based on a combination of theories is dangerous, but the foregoing is advanced only as a guide or a working hypothesis.

RUSSELL S. TARR

702 NATIONAL BANK OF COMMERCE BUILDING
TULSA, OKLAHOMA
January 16, 1934

## ANALYSES OF WOODBINE CORES FOR PRESENCE OF SALT WATER

In connection with drilling operations in the Woodbine formation in East Texas, cores have been taken of the sand and analyzed for chlorides to determine whether the sand contained salt water. Due to the low chloride content of cores from sands which apparently were water sands, the question was raised as to whether the water from the drilling fluid displaced the salt water present in the core. Through the coöperation of Paul L. Applin, it has been possible to show definitely that the water from the drilling fluid can displace the salt water present in the core.

A core having a porosity of 24.1 per cent and a chloride content of 0.01 per cent was obtained from a Woodbine well. Based on the porosity, 100 grams of core would contain 9 cubic centimeters of water. Therefore, the chloride content of the water saturating the core amounted to 1,100 parts per million. The water obtained from this sand when the well was tested showed 28,200 parts per million of chloride.

The thoroughness with which the water from the drilling fluid displaces the salt water in the core is probably dependent upon the diameter of the core, porosity of the sand, length of time required to obtain the core, character, rate of circulation and pressure of drilling fluid, and type of core barrel. This view is substantiated by the fact that variations occur in different wells in the ratio of chloride obtained in the water in the core to the chloride obtained in the water actually produced. As an example, this ratio in the illustration given above is 1 to 26, while in another well where the chloride content of the water in the core was 20,000 parts per million and the chloride content of the water actually produced was 60,000 parts per million, the ratio was 1 to 3.

R. H. Fash

Fort Worth, Texas
January 19, 1934

BULLETIN OF THE AMERICAN ASSOCIATION OF PETROLEUM GEOLOGISTS
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# DISCUSSION

## AGE OF SO-CALLED HUNTON LIMESTONE OF SOUTHERN McPHERSON AND NORTHWEST HARVEY COUNTIES, KANSAS

Raymond C. Moore[1] referred to a sample core sent to him by Charles Ryniker, taken from the Gypsy Oil Company's Hege No. 1, Sec. 13, T. 22 S., R. 2 W., Harvey County, Kansas, as possessing characteristics of a Silurian dolomite and containing fossil fragments of probable Devonian age. He was inclined to lean toward the Silurian age of the core material.

The formation classed as Siluro-Devonian from the Hege No. 1 was found from 3,330 to 3,410 feet and was described from samples by Arthur Price[2] as follows.

3,330 to 3,335—Trace brown sugary dolomite with white, crystalline and glauconitic limestone
3,335 to 3,353—Limestone, crystalline to coarse crystalline, slightly glauconitic with paper-thin seams of green shale
3,353 to 3,372—Limestone, crystalline; slightly glauconitic
3,372 to 3,378—Dolomite, soft, porous, and sugary
3,378 to 3,400—Dolomite, light brown and white, sugary, fossiliferous. A few bands of light gray chert. Salty taste and sulphurous odor
3,400 to 3,410—Dolomite as above

An almost perfect cast of a *Cyrtina* species was recovered from the core taken from 3,378 to 3,400 feet. It was tentatively identified by Ryniker as either *Cyrtina hamiltonensis* (Hall) or *Cyrtina missouriensis* (Swallow). These fossils occur in the Devonian of Missouri.

Since the date of completion of the Hege No. 1, the Hollow pool of T. 22 S., R. 3 W., has been discovered. Numerous cores of the so-called Hunton limestone have been recovered. They show a formation composed essentially of two members: the upper, white coarsely crystalline, in places crinoidal limestone; and the lower, dense to finely crystalline, porous, brown dolomite. The lower member is the productive horizon. There is considerable irregularity in thickness of both members from location to location.

A core from the Stanolind-Amerada's Froese No. 1, SW. $\frac{1}{4}$, NW. $\frac{1}{4}$, Sec. 20, T. 22 S., R. 3 W., taken from 3,485 to 3,491 feet, shows highly crystalline, crinoidal limestone, containing fragments of corals and brachiopods. At least two types of corals are present: one a *Favosites* species, and the other an unidentified cup coral. The top of the brown, dense dolomite was cored from 3,491 to 3,496 feet. No fossils were noted in this oil-saturated core.

The age of the so-called Hunton of the Hollow pool remains doubtful. The lithology of the two members is suggestive of the Callaway or Mineola above and the Cooper below (Missouri Devonian). The freakish occurrence of the two members is suggestive of an unconformity between them although it may be due to the pre-Chattanooga folding and erosion to which these formations were subjected.

ROY HALL

WICHITA, KANSAS
December 20, 1933

[1] Personal communication to Charles Ryniker.

[2] Personal communication.

BULLETIN OF THE AMERICAN ASSOCIATION OF PETROLEUM GEOLOGISTS
VOL. 18, NO. 2 (FEBRUARY, 1934), PP. 267-272

# REVIEWS AND NEW PUBLICATIONS

*On the Mineralogy of Sedimentary Rocks—A Series of Essays and a Bibliography*. P. G. H. Boswell (Thomas Murby & Co., 1 Fleet Lane, E. C. 4, London, 1933). 393 pp. Demy, 8 vo. Price, 21/—net: about $5.40.

This book is a compilation of all the published papers dealing with the mineralogy of sedimentary rocks. The text of the book is a series of general essays giving the results of investigations carried on by many workers. To this the writer has added comments and conclusions of his own. The essays in general are elementary but do bring to the reader's attention many subjects of interest. Boswell gives a complete history of investigations in the first chapter, and thereafter confines his essays to brief chapters dealing with the mineralogy of sedimentary rocks. Under the chapter heading "Individuality of Sediments," he discusses the value of mineral assemblages in the identification of rock samples and the aid such assemblages provide in referring a rock sample to its stratigraphical horizon and general geographical location. In treating of the stability of minerals some interesting and instructive information is provided concerning the physical and chemical properties of sedimentary rocks—their solubility and general stability under laboratory tests.

Boswell has set out 12 principles under "Minerals as Clues to the Source of Sediments," which he finds are generally applicable to the distribution of heavy minerals. The 12 principles appear to be those which any careful worker would consider before forming conclusions regarding the source of sediments. The 12 principles are all illustrated by results obtained in the British Isles. The background of the book is almost entirely confined to the British Isles with but an occasional reference to the results of Mid-Continent workers.

The book deals in sequence with "Sand Dunes," "Deep Sea Sediments," "Detrital Minerals," "Mineral Composition of Clays," and the "Detrital Minerals and the Origin of Metamorphic Rocks." Each subject is discussed briefly with the conclusions of various workers cited to illustrate the writer's conclusions.

The bibliography and abstracts covering 1,019 publications make the book of value to the worker in sediments. The abstracts briefly give the conclusions of each writer and cover the publications of all nations.

The book has a general index, an index of stratigraphical horizons, an index to localities, an index to minerals, an index to figured minerals, and an index to technique.

The book is well written and edited. Many of the papers included in the bibliography have been abstracted and published in the *Proceedings of the Liverpool Geological Society* and are here collected and brought up to date in one volume.

G. S. Dillé

Tulsa, Oklahoma
December 29, 1933

*The Jurassic System in Great Britain.* By W. J. ARKELL. Oxford, England, 1933. 681 pp., 41 pls. Price, $7.75.

As the birthplace of stratigraphic geology, and the scene of many of its outstanding subsequent developments, the broad belt of Jurassic rocks in England is famous throughout the world. This fact furnishes one reason for welcoming Arkell's large, well printed, and beautifully illustrated volume. A little study of the volume furnishes additional reasons, some of which will be obvious from a summarized catalogue of its contents.

Forty-one plates, 11 showing important zone fossils, mostly ammonites and ostracods
A chapter (Chapter I) on the classification of Jurassic rocks and on zoning in general
Two chapters on tectonics and its relation to Jurassic sedimentation
Fourteen well organized chapters on Jurassic stratigraphy
A final chapter on Jurassic paleogeography
Appendices on coral reefs, geosynclines, peneplains, and Jurassic stage-names
A bibliography of 47 pages

The first chapter, on classification, gives an interesting account of William Smith and his meeting with two clerical friends who already knew the names of many Jurassic fossils but had not realized their stratigraphic importance. Smith, with the advice and assistance of these friends, prepared a chart of stratal terms for the Jurassic succession in 1813.

In an attempt to escape difficulties with facies, A. d'Orbigny, between 1842 and 1849, introduced ten stage names. Each stage was separated from overlying and underlying stages by "the annihilation of life-forms and its replacement by another." Even before 1859, however, Quenstedt pointed out serious weaknesses in d'Orbigny's work. Weaknesses still remain in the work of his successors, moreover, although d'Orbigny's ten original Jurassic stages have now been increased to about one hundred.

Oppel, a pupil of Quenstedt's, who died at the age of 34 in 1865, classified the Jurassic of Germany, France, and England on the basis of *zones*, or "belts of strata, each of which is characterized by an assemblage of organic remains, of which one abundant and characteristic form is chosen as index" (Marr). This zone concept is probably the most useful stratigraphic tool ever devised, but something about it, possibly the method of choosing names, has led to much confusion in applying it and reasoning about it. Buckman called these zones "faunizones," Diner "Faunenzonen."

In 1893 S. S. Buckman introduced another concept, also useful in many ways, that of the *hemera*, the smallest time-division recognizable paleontologically where maximum sections are found. The best rock term proposed for the beds deposited during a hemera is *epibole* (Trueman).

One of the most interesting features of this chapter is Arkell's discussion of Buckman's work. He feels that the early work, based on Buckman's own intensive field investigations, is excellent; that part of his later work is woefully bad, and is almost inextricably interwoven with good work; and finally, that the "polyhemeral" system seems unlikely to serve as the basis for worldwide correlations. For practical stratigraphy, as a matter of fact, he believes that Oppel's zones, the "*faunizones*" of Buckman, have many advantages.

It would be easy to linger over this first chapter, to discuss "*biozones*,"

"*Teilzones*," and "*Teilchrons*," but it seems better to hasten on, and refer the curious to Arkell's own discussion.

One impression gained from reading the structural chapters is that a large amount of important regional data has been secured by the drilling of a few wells in southeastern England. There can be no doubt that well drillers rank high among the friends of stratigraphic geology. A series of interesting maps shows the present shape of the Paleozoic platform beneath the Jurassic, the deformation of the Gault, the eastward overlap of Jurassic strata, and other important relations. The cyclical nature of Jurassic sedimentation is explained, with references to the work of Frebold and Stille.

The third chapter contains an illuminating account of the development of the Jurassic basins of deposition, and of the "axes of uplift" within them. Stille's views as to orogenic and epeirogenic processes are taken as the foundation for Arkell's discussion of warpings, foldings, transgressions, and regressions.

The stratigraphic part of the book is so well organized and so well illustrated by plates and diagrams that its rather formidable bulk fails to deter.

The final chapter deals with paleogeography, "the most fascinating but at the same time the most dangerous part of our subject." Arkell finds a curious contrast between the distribution of corals and ammonites, and decides that ammonites avoided coral seas. This view alters some paleogeographic concepts that have been held by certain earlier workers. He discusses the problem of sea-boundaries at different stages, and maps them for two stages, Lower Lias and Bathonian.

> Around the margins of the land the seas transgressed and regressed with an unceasing ebb and flow, as in one age subsidence exceeded elevation and in another elevation overcame subsidence. On the whole, however, the upward tendency prevailed on the land and the downward in the troughs, until in the end the centers of the troughs had subsided between 3,000 and 4,000 feet, and they had become filled with the richly-fossiliferous and inexhaustibly interesting series of varied sediments which we call the Jurassic system.

Most American geologists whose work involves stratigraphy have no doubt long intended to make a serious study some day of the literature of the British Jurassic. The majority of them, it is likely, have not yet made it. If so, they are fortunate because they can now succeed better by reading a single book than they could have done formerly even by toiling through a very long shelf of books and special publications.

R. D. REED

LOS ANGELES, CALIFORNIA
January 3, 1934

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"Origin of the Anhydrite Cap Rock of American Salt Domes." By MARCUS I. GOLDMAN. *U. S. Geol. Survey Prof. Paper 175-D* (1933). Pp. 83–114; 45 figs. Supt. Documents, Washington, D.C. Price, $0.15.

This paper represents Dr. Goldman's conclusions after more than ten years of study (mainly petrographic) and meditation on the cap rock of Texas-Louisiana salt domes. In a preliminary, now old, paper he advocated a sedimentary origin for the anhydrite-gypsum cap rock. He now concludes that "it is formed by the cementation and consolidation on top of the salt stock, of grains of anhydrite and fragments of anhydrite rock freed from the salt stock by solution of its upper end."

His argument is as follows.

A. The truncation of the folds in the salt by the relatively flat salt table and the overlying anhydrite gypsum is outstanding and most weighty geologic evidence of the residual origin of the cap rock. On some of the German domes, a tilted bed of salt embedded in the salt merges into the cap at the salt table.

B. The presence of a layer of water and anhydrite sand between the top of the salt and bottom of the cap rock on certain domes is strong support for the "residual" interpretation of the cap.

C. The anhydrite rather commonly consists of a breccia of fine-grained white banded fragments in a matrix of coarser grains. That character of the cap rock excludes the possibility that the cap rock is an original undisturbed bed of sedimentary anhydrite pushed up by the salt from depth, and indicates two alternatives to be considered: (1) that the cap rock is a residual accumulation; or (2) that it is a completely brecciated and re-cemented original bed of sedimentary anhydrite.

D. The parallel (katatectic) banding is most readily explained by the formation of the cap by residual accumulation in the following manner:

1. The process starts with solution of the unprotected top of the salt core by water at the surface or from some bed which has been penetrated.

2. Once a protective cap has been formed, it is assumed that in some way water from the same or different source finds its way along the contact (the reviewer strongly doubts the validity of the assumption) and salt continues to be dissolved.

3. Various factors tend to preserve for a time an open space between the cap rock and the top of the salt core as the solution proceeds. Support to the cap rock would be given by the thicker of the folded beds of solid anhydrite in the salt (they are few and far between in the Gulf Coast domes). By solution of the salt, these beds would be left projecting up into the brine-filled space between the salt and cap rock. The residual crystals of anhydrite which were disseminated through the salt collect in a layer at the bottom of the layer of brine. The weight of the overlying cap and overburden crushes down the ends of sedimentary anhydrite which project up from the salt and compacts the whole mass of residual anhydrite sand grains and debris of the crushed bedded anhydrite. Recrystallization by solution and deposition produces cementation.

4. Solution continues and the process is repeated.

5. The periodicity of the process produces the katatectic banding. (This process seems wholly improbable to the reviewer.)

Three other alternative explanations of the katatectic banding are possible.

1. Some process of diffusion. This explanation is untenable, for the dividing surfaces do not cut the breccia fragments and are of mechanical weakness.

2. Stratification. The presence of the coarse-grained matrix throughout the cap rock practically eliminates this explanation.

3. Shearing. He states that unless the katatectic surfaces can be proved not to be shearing surfaces, there is no conclusive internal petrographic evidence of the residual origin of the anhydrite.

The argument for the "residual" rather than "shearing" origin is as follows.

1. There is little crushing along the katatectic surfaces.
2. Shearing should produce vaguely curving flow-like lenticular structure rather than the actual parallel banding.
3. It is difficult to conceive of any force connected with salt domes that would be able to produce such horizontal surfaces by shearing, particularly in such a place as at the contact with salt in the Hockley salt shaft.
4. The irregularity of some of the katatectic surfaces could not conceivably result from shearing.

E. The rather common thickening of the cap toward the center of the dome fits well with the "residual" theory, for:

1. Upward flow of the salt should be most rapid in the center of the dome (that is contrary to the results of Escher and Kuenen's experiments); to form a flat salt table, the greatest amount of solution would, therefore, be at the center of the dome (the reviewer can not understand why in the Gulf Coast domes, solution should not be less in the center of the salt table than at the edges). The greatest accumulation of residual anhydrite should occur at the center. (The position of the cap at the head of a punch would seem to the reviewer sufficiently to explain the convex form of the cap.)

F. A satisfactory hypothesis of the origin of the anhydrite cap must explain its absence on some domes. The absence is explained more easily under the "sedimentary" theory. Under the "residual" theory, it would be explained by:

1. Solution of the anhydrite-gypsum;
2. Original paucity of anhydrite in the salt;
3. The youthfulness of the dome.

The reviewer is still agnostic in regard to the origin of the cap rock. Even after many a friendly argument with Goldman and after careful study of this paper, the "sedimentary" theory is not satisfactory to the reviewer, but he is still less satisfied with the "residual" theory. The salt table which to Goldman is one of the strongest evidences of the "residual" theory presents to the reviewer one of the greatest difficulties to his acceptance of that theory for the American domes. The formation of a salt table when the salt extends to or above the surface can be envisaged by the reviewer but the contact of the salt and anhydrite cap on such domes as Hockley and Sulphur can never have been near the surface. For such domes, he can see every reason why solution should be greatest at the edge of the table and should tend to produce a rounded top.[1]

DONALD C. BARTON

HOUSTON, TEXAS
December 20, 1933

[1] For further discussion by Goldman of the problem of solution, see also, "Bearing of Cap Rock on Subsidence on Clay Creek Salt Dome, Washington County, Texas, and Chestnut Dome, Natchitoches Parish, Louisiana," this *Bulletin*, Vol. 15, No. 9 (September, 1931), pp. 1105–13.

## RECENT PUBLICATIONS

### AFRICA

"Zur Tektonik des mittleren Südwestafrika" (Tectonics of Central Southwest Africa), by T. W. Gevers. *Geol. Rund.* (Gebrüder Borntraeger, Berlin), Vol. 24, No. 6 (1933), pp. 337–48.

### CALIFORNIA

"Report on North Belridge Oil Field," by H. M. Preston, *Summary of Operations, California Oil Fields* (San Francisco), Vol. 18, No. 1 (July, August, September, 1932). Published at end of 1933. Pp. 5–24; 3 pls.

### GENERAL

*Ore Deposits of the Western States*, by many authors. Edited by the Committee on the Lindgren Volume. Published by the American Institute of Mining and Metallurgical Engineers; sponsored by the Rocky Mountain Fund. 29 West 39th Street, New York, N.Y. (1933). 797 pp. Illus. Cloth. 6×9 inches. Price: domestic postpaid, $5.00; foreign postpaid, $5.60.

### GERMANY

"Sedimentationsprobleme in der Germanischen Senke zur Perm- und Triaszeit" (Sedimentation Problems in Permo-Trias of Germany), by Martin Wilmarth. *Geol. Rund.* (Berlin), Vol. 24, No. 6 (1933), pp. 349–77.

### ILLINOIS

"Oil and Gas Possibilities of Parts of Jersey, Greene, and Madison Counties," by D. M. Collingwood, with appended well records compiled and correlated by George E. Ekblaw and L. E. Workman. *Illinois State Geol. Survey Rept. Investigation 30* (Urbana, 1933). 91 pp., 4 figs., 3 pls.

### IRAK

*Gisements pétrolifères de l'Irak* (Petroleum in Irak), by C. P. Nicolesco. Les Presses Modernes, 45, Rue de Maubeuge, Paris (1933). 221 pp., 18 figs. 6.5×10 inches.

### MONTANA

"Border-Red Coulee Oil and Gas Field, Toole County, Montana, and Alberta, Canada," by Charles S. Erdmann and John R. Schwabrow. *U. S. Geol. Survey* report released for public inspection and consultation in Survey offices at Casper, Wyoming; Denver, Colorado; Shelby, Montana; Billings, Montana; and Washington, D.C. Well illustrated report on geology and engineering problems. Contains structure-contour map on base of Virgelle member of Eagle sandstone.

### RUSSIA

"Emba Oil-Bearing Region," by N. A. Chromov. *The Petroleum Industry* (Moscow), No. 8 (1933), pp. 137–41. Structure contour map and section. Issued by the Petroleum Section of the Chief Fuel Department of the Peoples Commisariat for Heavy Industry. In Russian.

### TENNESSEE

"Ground-Water Resources of Western Tennessee," by F. G. Wells. *U. S. Geol. Survey Water-Supply Paper 656* (1933). Prepared in coöperation with the

Tennessee Division of Geology. Describes portion of state lying in Coastal Plain. Supt. Documents, Washington, D.C. Price, paper, $0.60.

TEXAS

"Ground-Water Resources in the Houston District, Texas," by W. N. White and Penn P. Livingston. Report of investigations in progress through past 3 years by coöperation between *U. S. Geol. Survey* and *Texas State Board of Water Engineers.* Records released for public inspection at Washington, D.C., and at Austin, Texas.

## RADIOACTIVITY OF SOIL GASES

### CORRECTION

In the article, "Radioactivity of Soil Gases," by Lynn G. Howell, published in the January *Bulletin*, the following corrections should be made.

Page 63, line 1 of the Abstract, should read: "The *alpha*-ray activity of the radon . . . . "

Page 65, line 1 of the second new paragraph, should read: "The electroscope for measuring the *alpha*-ray activity . . . ."

BULLETIN OF THE AMERICAN ASSOCIATION OF PETROLEUM GEOLOGISTS
VOL. 18, NO. 2 (FEBRUARY, 1934), PP. 274-276

# THE ASSOCIATION ROUND TABLE

## MEMBERSHIP APPLICATIONS APPROVED FOR PUBLICATION

The executive committee has approved for publication the names of the following candidates for membership in the Association. This does not constitute an election, but places the names before the membership at large. If any member has information bearing on the qualifications of these nominees, he should send it promptly to J. P. D. Hull, business manager, Box 1852, Tulsa, Oklahoma. (Names of sponsors are placed beneath the name of each nominee.)

### FOR ACTIVE MEMBERSHIP

Francis Faulkner Campbell, Tulsa, Okla.
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Hubert Charles Igau, Houston, Tex.
Leslie A. Fisher, John C. Myers, A. T. Schwennesen
Jack Critz Pollard, Houston, Tex.
Geo. Edwin Dorsey, Dave P. Carlton, Henry C. Cortes

### FOR ASSOCIATE MEMBERSHIP

Charles D. Gleason, Rolla, Mo.
H. S. McQueen, H. A. Buehler, C. L. Dake

## NINETEENTH ANNUAL MEETING, DALLAS, MARCH 22-24

The nineteenth annual meeting of the Association will be held at the Baker Hotel, Dallas, Texas, March 22, 23, and 24. A preliminary announcement containing the list of committee chairmen was published in the January *Bulletin*, pages 154-55. The usual announcement with more details, particularly about transportation, hotels, and entertainment, is being mailed to each member this month.

The railroads are granting members, and dependent members of members' families, attractive round-trip rates of a fare and a third of current fares, with authorized diverse return routes, within a limit of 30 days in addition to date of sale. The special identification certificate and instructions are being mailed each member; however, members should ask local ticket agents about possible excursion rates even lower than the convention rate.

Field trips are being planned by bus to the Grand Saline salt mine, the Van field, the East Texas field, local outcrops of the Woodbine and associated formations, and possibly to the fault line fields. Tentative plans are being considered for an air flight over points of interest throughout East Texas.

Exhibit space for laboratory, office, and field equipment will be available on the Mezzanine, near the ballroom, where the technical program will be presented. There will also be space for members to display maps, charts, specimens, et cetera.

The technical program committee is endeavoring to allot more time for delivery and discussion,—possibly an hour for a single paper. For the satisfactory realization of this plan, the hearty coöperation of all members is expected, permitting the committee to use its judgment in selecting papers for oral presentation. Many manuscripts of the usual variety of subjects are solicited so that a full program may be presented and ample material made available for the *Bulletin*.

Titles of papers and abstracts not already submitted, together with information on number of double-spaced typewritten pages in manuscript, number of illustrations, and other data should be submitted in duplicate to F. H. Lahee, chairman of the technical program committee, Box 2880, Dallas, Texas, before March 1.

Members submitting complete manuscript prior to the meeting are requested to submit two or three duplicates for use in soliciting discussion to be prepared in advance of the meeting.

Paleontology titles, abstracts, and manuscripts, to be presented before the Society of Economic Paleontologists and Mineralogists, should reach secretary Gayle Scott, Texas Christian University, Fort Worth, Texas, not later than March 1.

Geophysics titles, abstracts, and manuscripts for the Society of Petroleum Geophysicists should reach editor L. W. Blau, Humble Oil and Refining Company, Houston, Texas, not later than March 1.

The following is a tentative list of papers for the program.

Ed. W. Owen and David Crawford, "Fault Systems of the Gulf Coastal Plain"
L. P. Teas and F. W. Michaux, "The Conroe and Tom Ball Fields"
M. G. Cheney, "The Geology of Well Spacing"
J. S. Hudnall, "The East Texas Field"
T. A. Link, "Petroleum Geology at the World's Fair"
O. E. Meinzer, "Movements of Underground Waters"
C. D. Avery, "Relationship of Geology to Unit Operation of Oil or Gas Fields Involving Government Lands"
Parker D. Trask and H. E. Hammar, "Source Beds in Mesozoic Rocks in California"
S. A. Thompson, "The Fredericksburg Division of the Lower Cretaceous, with Special Reference to North Texas"
O. C. Wheeler, "The Infantis and LaCira Oil Fields of Colombia"
O. L. Brace, "Estimating Oil Reserves"
George O. Williams *et al.*, "Recent Developments in Oklahoma"
N. W. Bass, "The Origin of the 'Bartlesville' Shoestring Sands of Eastern Kansas"
H. D. Miser, "The Carboniferous Rocks of the Ouachita Mountains"
S. Pirson, "Oil and Gas Possibilities of Belgium and of the Belgian Congo"
C. B. Read and T. A. Hendricks, "Correlation of the Pennsylvanian Strata in the Arkansas and Oklahoma Coal Fields"
C. E. Erdmann, "Geology of Whitlash Dome, Liberty County, Montana"
B. H. Parker, "The Cretaceous Geosyncline of the Rocky Mountain Region"
J. Harlan Johnson, "The Pennsylvanian and Permian of Colorado"
David White, "The Age of the Jackfork and Stanley Formation in the Ouachita Mountains, as Indicated by Plants"
M. A. Hanna and D. W. Gravell, "Larger Foraminifera from the Moody's Branch Marl, Jackson Eocene of Texas, Louisiana and Mississippi"
M. A. Hanna and D. W. Gravell, "Distinctive Foraminifera of the Oligocene of the Gulf Coast"
M. C. Israelsky, "Foraminifera of the Claiborne"
C. I. Alexander, "Ostracoda of the Midway Formation of Texas"

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BULLETIN OF THE AMERICAN ASSOCIATION OF PETROLEUM GEOLOGISTS
VOL. 18, NO. 2 (FEBRUARY, 1934), PP. 277-278

# Memorial

## JOHN R. ROBERTS

John R. Roberts succumbed to a heart attack at his desk in the San Francisco office of the United States Bureau of Internal Revenue on September 23, 1933. He was born in Superior, Wisconsin, on April 14, 1888. He is survived by his wife, Alice Hudson Roberts, and two children, Kathryn and John. The family reside at 1430 Arch Street, Berkeley, California.

John R. Roberts became a member of The American Association of Petroleum Geologists in June, 1919. He had prepared himself for his life work by taking advanced courses in geology at the University of Wisconsin from 1913 to 1915. Previous to this he had been in charge of a magnetic survey and diamond-drill exploration test of the Vermilion Iron Range in the Lake Superior region. Subsequently he was a geologist with the Wisconsin Geological Survey. After a period of consulting work with John E. Andrus in Minneapolis, Minnesota, he became identified with the University of Texas in 1918 as a geologist in the Bureau of Economic Geology and Technology, preparing a report on manganese. He is the author of "Geology of Val Verde County, Texas" (University of Texas Bulletin).

John wore the uniform of his country as a private in 3rd Company, Coast Artillery, U.S.A., in 1905.

In 1919 he was a geologist with The Texas Company and then resumed practice as a consulting geologist in Eastland, Texas, from 1920 to 1922. In 1922 he entered the Oil and Gas Division, Income Tax Unit, Treasury Department, at Washington, D.C. He became one of the outstanding engineers in the Bureau of Internal Revenue and in 1925 was assigned to the important San Francisco district and placed in full charge of the valuation engineering work of that office. He became widely known for his able, conscientious, and impartial handling of serious valuation problems affecting the income tax cases of California oil operators.

John R. Roberts was also a member of the American Institute of Mining and Metallurgical Engineers and of the American Association for the Advancement of Science. He was a Scottish Rite Mason and a Shriner.

John was a large and well built man physically, and his qualities of mind and character matched his build. He was kindly, genial, and remarkably understanding. He leaves a host of friends in California, Washington, D.C., Texas, and Wisconsin, who will hold him in affectionate memory.

LOUIS H. EVANS

LOS ANGELES
December 6, 1933

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## IRVING McKAY STREETER

Irving McKay Streeter, a geologist for the Venezuela Gulf Oil Company, was lost overboard from one of the company tankers in the Atlantic Ocean off Haiti, the night of October 30, 1933. He was on his way to the United States to join his family on a well deserved vacation. His loss came as a distinct shock to his family and to his many friends in Venezuela.

Mr. Streeter was born, January 9, 1898, at Benkleman, Nebraska. He attended the University of Cincinnati from 1920 to 1926; four years in undergraduate work, and two years in post-graduate work. He majored in geology and received an A.B. degree. He joined the geological department of the Venezuela Gulf Oil Company on July 7, 1926, and continued in geological work for this company until his death. For some time previous he was the resident subsurface geologist for the Bolivar coastal fields. He has been an active member of The American Association of Petroleum Geologists since October 6, 1930. Mr. Streeter served for a short period in the U.S. Army during the World War, entering service on October 3, 1918, and being honorably discharged on April 9, 1919.

Irving was a quiet, studious individual, and a very conscientious worker. His whole existence was centered in his family and in his work. One of his chief amusements was hunting.

He is survived by his wife, Mrs. Helen M. Streeter, of 1522 Pullan Avenue, Cincinnati, Ohio, and a son, age 4 months; also by his mother, Mrs. Emma W. Streeter, and a brother, E. D. Streeter, both of Westfield, New Jersey.

His death has been a distinct loss to his associates.

P. E. Nolan

Maracaibo, Venezuela
December 21, 1933

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# AT HOME AND ABROAD

## CURRENT NEWS AND PERSONAL ITEMS OF THE PROFESSION

R. J. St. Germain, consulting geologist, formerly of Tulsa, Oklahoma, is now at 710 Sterling Building, Houston, Texas.

J. D. Hedley, geologist with Barnsdall Oil Company, has been transferred from Houston, Texas, to Thibodaux, Louisiana. His address is the Jeffries Hotel.

Warren B. Weeks, formerly with the firm of Bale, Evans and Weeks, is now microscopist with the Phillips Petroleum Company, Bartlesville, Oklahoma.

J. J. Russell, Jr., formerly of Merkel, Texas, has accepted a position with the Texas Pacific Coal and Oil Company, Midland, Texas.

Hugh L. Burchfiel, formerly of Midland, Texas, is doing some work for The California Company in the Persian Gulf. His address is in care of the Bahrein Petroleum Company, Bahrein Island, Persian Gulf. He expects to be there three years.

John S. Redfield, of the Shell Petroleum Corporation, Tulsa, and Miss Maudie Stacy, of the Ponca City High School faculty, were married on December 23, 1933, at the First Presbyterian Church, Ponca City. They will be at home in Tulsa, Oklahoma, in February.

The Tulsa Geological Society has issued a publication, *Tulsa Geological Society Digest* (1933), made up of digests of the 17 papers presented before the society during the year. The new annual contains 60 pages of text and 23 pages of advertising (including 3 cover pages). The cover is heavy paper stock, 6×9 inches. The book appeared under the administration of the following officers: Ira H. Cram, president; John L. Ferguson, first vice-president; Ed. F. Shea, second vice-president; Stanley B. White, secretary-treasurer; Shepard W. Lowman, editor. Non-members of the society may obtain copies, at $0.50 each, from the secretary-treasurer, T. H. Newman, Skelly Oil Company, Tulsa, Oklahoma.

Ira H. Cram, division geologist of the southwestern division of The Pure Oil Company, delivered the presidential address, "A Study of Faults in Oklahoma," before the Tulsa Geological Society at the annual meeting, January 8, 1933. The following were elected officers for the year 1934: president, E. F. Shea, Stanolind Oil and Gas Company; first vice-president, J. B. Leiser, Shell Petroleum Corporation; second vice-president, K. K. Kimball, consulting geologist; secretary-treasurer, T. F. Newman, Skelly Oil Company; editor, Glenn Scott Dillé, The Texas Company; new councilors, Robert E. Garrett, consulting geologist; L. Murray Newmann, Carter Oil Company; Sam H. Woods, Twin State Oil Company.

V. H. McNutt presented a paper, "A Birdseye View of American Potash," before the San Antonio Geological Society on January 8.

At the December meeting of the Committee on Grants-in-Aid of the National Research Council the following grants were made in the field of geology and geography: GEORGE H. ANDERSON, research fellow in geology, California Institute of Technology, "Alternations and Replacements Occurring in a Granite Batholith in the Inyo-White Mountain Range of California-Nevada"; ELMER H. JOHNSON, industrial geographer, Bureau of Business Research, University of Texas, "Physical and Economic Characteristics of Natural Areas of the Southwest Gulf Region"; CHRISTINA LOCHMAN, Chicago, Illinois, "The Fauna of the Upper Cambrian Cap Mountain Formation of Texas"; EDWIN T. MCKNIGHT, associate geologist, United States Geological Survey, "Igneous Complex at Prospect Mountain, near Litchfield, Connecticut"; W. A. TARR, professor of geology, University of Missouri, "Chemical and Bacteriological Studies of the Lead Deposits of Southeastern Missouri." The National Research Council, Washington, D. C., will be ready to consider further requests for research assistance this spring. Applications should be made on forms which will be furnished by the secretary of the Committee on Grants-in-Aid on request. All applications must be on file with the committee by March 15, 1934. Action upon these applications will be taken about the middle of May.

The correct address of R. J. METCALF, geologist for the Mid-Kansas Oil and Gas Company, is 1415 Milam Building, San Antonio, Texas.

The Midland (Texas) Geological Luncheon Club has changed its name to the Midland Geological Society. CHARLES A. MIX, of the California Oil Company, is president, and ALDEN S. DONNELLY, of the Honolulu Oil Company, is secretary-treasurer.

A special committee of the Pacific Section of the Association consisting of JOHN P. BUWALDA, chairman; A. ARTHUR CURTICE, president; WILBUR D. RANKIN, secretary-treasurer; and GRAHAM B. MOODY, has issued a statement expressing the practically unanimous conviction of the Section that "destructive earthquakes are to be expected in southern California from time to time in the future, as in the past, and that in the design of new buildings, in the strengthening of existing structures, and in the revision of building codes provision should be made against the occurrence of an earthquake or earthquakes, sooner or later among shocks of lesser severity, of the magnitude and intensity of the San Francisco disturbance of 1906." Evidence on which the statement is based is set forth. "Fortunately earthquakes constitute a hazard against which it is entirely feasible to safeguard a community, in contrast with the natural hazards which affect some other parts of the country."

A. H. GARNER has resigned from the firm of Brokaw, Dixon, Garner, and McKee, petroleum engineers, New York City, and announces the opening of an office at Suite 2715, 120 Broadway, New York, N. Y.

P. H. BOHART, formerly of Apartado 106, Tampico, Mexico, may now be addressed at the Gypsy Oil Company, Box 661, Tulsa, Okla.

JO PAT BLACK has resigned from the Gulf Research and Development Corporation to take charge of torsion-balance work for the Republic Production Company, of Houston, Texas. His headquarters will be 2365 Orange Street, Beaumont, Texas.

Marvin Lee, geologist and technical adviser to the oil advisory committee of the Kansas Corporation Commission, Wichita, was seriously injured in an automobile accident south of Emporia, Kansas, in January.

Shirley L. Mason, of Bethlehem, Pennsylvania, sailed for South America about the middle of January to do field work for the Venezuela Gulf Oil Company. His address is Apartado 35, Ciudad Bolivar, Venezuela.

O. E. Nordman has changed his address from 1308 W. First Street, Perry, Oklahoma, to 829 East Fifteenth Street, Ada, Oklahoma.

Gage V. Lund, geologist with the California Company, has moved from Dallas to Victoria, Texas. His address is Box 486.

R. A. Brant, geologist with the Atlantic Oil Producing Company, Tulsa, spoke before the Tulsa Geological Society, January 22, on "Problems of Mayes and Boone in Oklahoma."

James B. Dorr, formerly with the Huasteca Petroleum Company, Tampico, Mexico, is now with the Shell Petroleum Corporation, Box 2099, Houston, Texas.

Virgil B. Cole, formerly of Box 143, Perry, Oklahoma, is now at 211 South Center, Ada, Oklahoma.

The Rocky Mountain Association of Petroleum Geologists held a special meeting, January 22, at Denver, Colorado. The principal talk of the evening was by H. H. Nininger on "Importance and Recognition of Meteorites." New officers elected January 8 include: president, H. F. Davies; first vice-president, W. A. Waldschmidt; second vice-president, H. A. Aurand; secretary, C. E. Erdmann.

Cecil Hagen, formerly of Laredo, Texas, is now in charge of the land and geological department for the Feltex Oil Corporation, Gulf Building, Houston, Texas. Hagen recently made an inspection trip of the San Juan Basin, New Mexico, for his company.

R. B. Roark, production manager for the north half of the Mid-Continent field, for Shell Petroleum Corporation, Tulsa, left January 26 for The Hague, Holland, to confer with the Royal Dutch Shell and familiarize himself with the policies of the world-wide combine. He was accompanied by Mrs. Roark.

J. T. Richards, geologist with the Gypsy Oil Company, has returned to Oklahoma City, after spending a year at Seminole, Oklahoma. His address is 901 Petroleum Building.

John W. Cushing has changed his address from Sistersville, West Virginia, to the Wiser Oil Company, Bartlesville, Oklahoma.

E. H. McCullough is in charge of the recently opened California office of the Amerada Petroleum Corporation at 522 Subway Terminal Building, Los Angeles.

D. M. Secor, geologist, formerly with the Houston Oil Company, has joined the Skelly Oil Company, with headquarters at Houston, Texas.

CLARK R. STEINBERGER, for the past seven years geologist with the Ohio Oil Company, with headquarters at Owensboro, Kentucky, has moved to Houston and will be associated with his father, brothers, and C. W. Wheeler in the Steinberger Petroleum Company, with offices in the Sterling Building.

At the regular meeting held December 11, the Appalachian Geological Society, Charleston, West Virginia, elected for the year 1934 the following officers: president, O. FISCHER, Box 1375; vice-president, P. E. DUFENDACH, Kentucky-West Virginia Gas Company, Ashland, Kentucky; secretary-treasurer, ROBERT C. LAFFERTY, Columbian Carbon Company.

At a recent meeting the Fort Worth Geological Society elected the following officers: president, FRANK A. HERALD, Fort Worth National Bank Building; vice-president, CLAUDE F. DALLY, Fort Worth National Bank Building; secretary-treasurer, THOMAS B. ROMINE, Texas Pacific Coal and Oil Company.